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**Engineering Studies Related to the Skylab Program**

**FINAL REPORT FOR TASK H:**

**Microwave/Optical/Infrared Image Processing for  
Ocean Current Recognition**

by

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Image Processing for Ocean Current Recognition

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Enclosure

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## 1. INTRODUCTION AND SUMMARY OF RESULTS

This report covers the work done and results obtained under Task H of contract NAS6-2307 sponsored by the Wallops Flight Center of NASA. This task had as its objectives three defined goals: (1) to serve as a "pre-cursor" to an investigation to be conducted as part of the GEOS-C program, in which GEOS-C radar altimeter data will be analyzed to reveal ocean current related surface topography, (2) to determine the value of satellite IR and visual radiometer data as potential sources of "ground-truth" data to help in analysis and interpretations of radar altimeter data, in order to aid the instrumentation planners for the SEASAT program, and (3) to determine whether optimal data reduction techniques would reveal clues on Gulf Stream topographic signature characteristics when applied to data from the S-193 radar altimeter on Skylab, even though it was recognized that this might be fruitless in view of the fact that the S-193 tracker rms noise level was about the same magnitude as the expected topography change due to the Gulf Stream Current.

The study was conducted in three basic steps: (a) a selection of promising looking Skylab passes was made from SL-2, 3 and 4 missions, (b) for those passes selected, an attempt was made to find ground truth IR and/or visual data for the same time period and geographic location from other satellites, surface observations, or aircraft measurements, and (c) the data from the altimeter was processed and examined for Gulf Stream topography indications in regions established using the ground-truth data. Section 2 of this report covers step (a) above, Section 3 covers step (b), and Sections 4 and 5 contain details on the work done in step (c).

Section 6 summarizes the results obtained which apply to objective (1) above - that of precursor to the GEOS-C investigation. Briefly, these results were:

- more directly repetitive altimeter "data takes" on a given surface feature are required than were available on Skylab,
- altitude tracker noise level must be reduced to improve chances of success - this goal should be realized in GEOS-C which will carry an altimeter with better precision than the S-193 by at least a factor of two,
- the altimeter will have to serve as its own source of fine grain geoidal information since there is so much uncertainty in existing geoid estimates,

even in the large scale features -- data from repetitive passes will have to be used to establish which features are fixed and therefore geoidal and which are dynamic and therefore attributable to ocean currents

- the single-pass surface topography observable could be something unexpected, since existing models of Gulf Stream surface topography are derived from data taken over time periods long with respect to the few seconds of observation time in a single satellite over-flight, and because IR images of the western thermal boundary of the Gulf Stream tend to be time variable and complex, particularly in the geographic region northeast of Cape Hatteras where the Gulf Stream is "free" of coastal and bottom effects

- there is no method currently in existence of establishing a relationship between the surface thermal boundary from an IR image or surface temperature measurement contours and the relative location or configuration of the surface topographic feature attributable to an ocean current. These two sets of observations (thermal and physical) are completely different phenomena which are affected in different ways by environmental conditions and instrument error sources.

With respect to objective (2) cited above - the determination of the value of ground-truth sensors accompanying the radar altimeter on SEASAT, the result reached is implicit in sections 4 and 5: unless the altimeter data reduction process reveals an obvious current-caused feature, the simultaneous IR/visual data is invaluable in establishing current location and boundary configuration to help in optimizing analysis of altimeter data. The only drawbacks to this conclusion are the already-mentioned uncertainty in the relationship between thermal and topographic signatures (which should result in minor location errors) and the problem of cloud contamination or obscuration of radiometer data. Neither of these is felt to warrant negation of the conclusion, however.

The results obtained in satisfaction of objective (3) above - the extraction of Gulf Stream topography from Skylab S-193 data - were inconclusive. The only two passes producing altimeter data which should have yielded comparable results (SL-2 Pass #9 and SL-3 Pass #3) turned out not to be comparable, possibly because in the SL-2 pass the altimeter was operated in Mode 5 and in the SL-3 pass the altimeter was in Mode 1.

After filtering, the calculated rms noise level in the altimeter data

was marginal insofar as detection of the expected Gulf Stream topography was concerned. As shown in Section 4, however, a possible indication of a topographical feature was found in SL-9 Pass 2 data, but the confidence level associated with it was quite low. The altimeter to be flown on GEOS-C should yield data with sufficiently lower noise (approximately 20cm at one/sec. data rate) that a comparison such as that attempted here should yield much better results if appropriate passes are made.

It should be pointed out that, for Skylab, the lack of overlapping passes with the altimeter in the same operating mode prevented reduction of measurement noise in the study reported here. Each successive directly overlapping pass could have been used to reduce noise level present in long-term static features.

As observed in Section 5, another reason that the altimeter data did not show more definitive Gulf Stream indications could have been anomalous behavior of the stream during the time period associated with the passes selected.

## 2. SELECTION OF SKYLAB PASSES AND ALTIMETER DATA

A total of eight passes were initially selected for use in this study, based on data from Johnson Space Center regarding geographic location of Skylab passes during which the S-193 altimeter was taking data in either Mode 1 or Mode 5. These are listed in Table 2-1. Maps showing the ground traces of these passes are given in Appendix A. Modes 1 and 5 are the primary operating modes of the altimeter for acquisition of altitude and waveform data. (A more detailed discussion of altimeter operating modes can be found in Reference 20.)

Referring to Appendix A, SL-3 EREP Passes #3 and #6 are seen to overfly the Gulf Stream -- #6 near Cape Hatteras and #3 off-shore from Wallops Flight Center. Since these traces did not show status of track, reference was made to another JSC publication, "EREP Sensor Data Acquisition Status Report for the Skylab SL-3 Mission". Using the approximate coordinates of the pass over-flight of the anticipated Gulf Stream location (latitude 35°N, longitude 75°W for Pass #6), the bracketing time period was found in the Status Report and altimeter operation noted. In this case, the report indicated that the altimeter was operated in Mode 1 beginning at GMT 13:46:30 at 38°N, 81°W; that track was good from that point until GMT 13:49:50 at 31°N, 69°W.

From SL-3, only EREP Pass #3 appeared to offer a good opportunity to extract the Gulf Stream surface characteristic from altitude data; Pass #6 was marginal insofar as ability to separate Gulf Stream effects from continental shelf effects, depending on just how far off-shore the stream was located at that time.

From SL-2, only EREP Pass #9 -- which almost reproduces the ground trace of EREP Pass #3 from SL-3 -- appeared to offer a good opportunity for Gulf Stream topography extraction. A plot of the ground traces of the two passes in the area of interest is provided in Figure 2-1. The other pass selected from SL-2, #4, was marginal due to the expected close-in-to-shore position of the stream where the trace crosses it.

Of the SL-4 selections, EREP Pass #32 appeared hopeful, but even in this case success was dependent on the exact location of the Gulf Stream at that time. The other SL-4 passes selected were marginal due to the expected close-to-shore location of the stream.

Pass #32 from SL-4 was attractive from a different point of view: its

TABLE 2-1

SKYLAB S-193 ALTIMETER DATATAKE GROUND TRACES OVER GULF STREAM

SL-2

<u>EREP Pass No.</u>	<u>Approx. GMT</u>	<u>DATE</u>	<u>D.O.Y.</u>	<u>MODE</u>	<u>APPROX. COORDINATES OF OVERHEAD POSITION</u>
4	17:11:00+	6-4-73	155	1	31°30'N, 80°30'W
9	13:01:30+	6-12-73	163	5	38°00'N, 75°30'W

SL-3

3	15:04:30+	8-5-73	217	1	38°00'N, 75°00'W
6	13:48:00+	8-9-73	221	1	35°00'N, 75°00'W

SL-4

4	16:38:40+	11-30-73	334	1	32°00'N, 80°00'W
30	20:44:30+	1-18-74	018	1	32°00'N, 80°30'W
32	19:18:03+	1-20-74	020	5	35°00'N, 75°00'W
37	19:29:30+	1-22-74	022	5	27°00'N, 79°00'W



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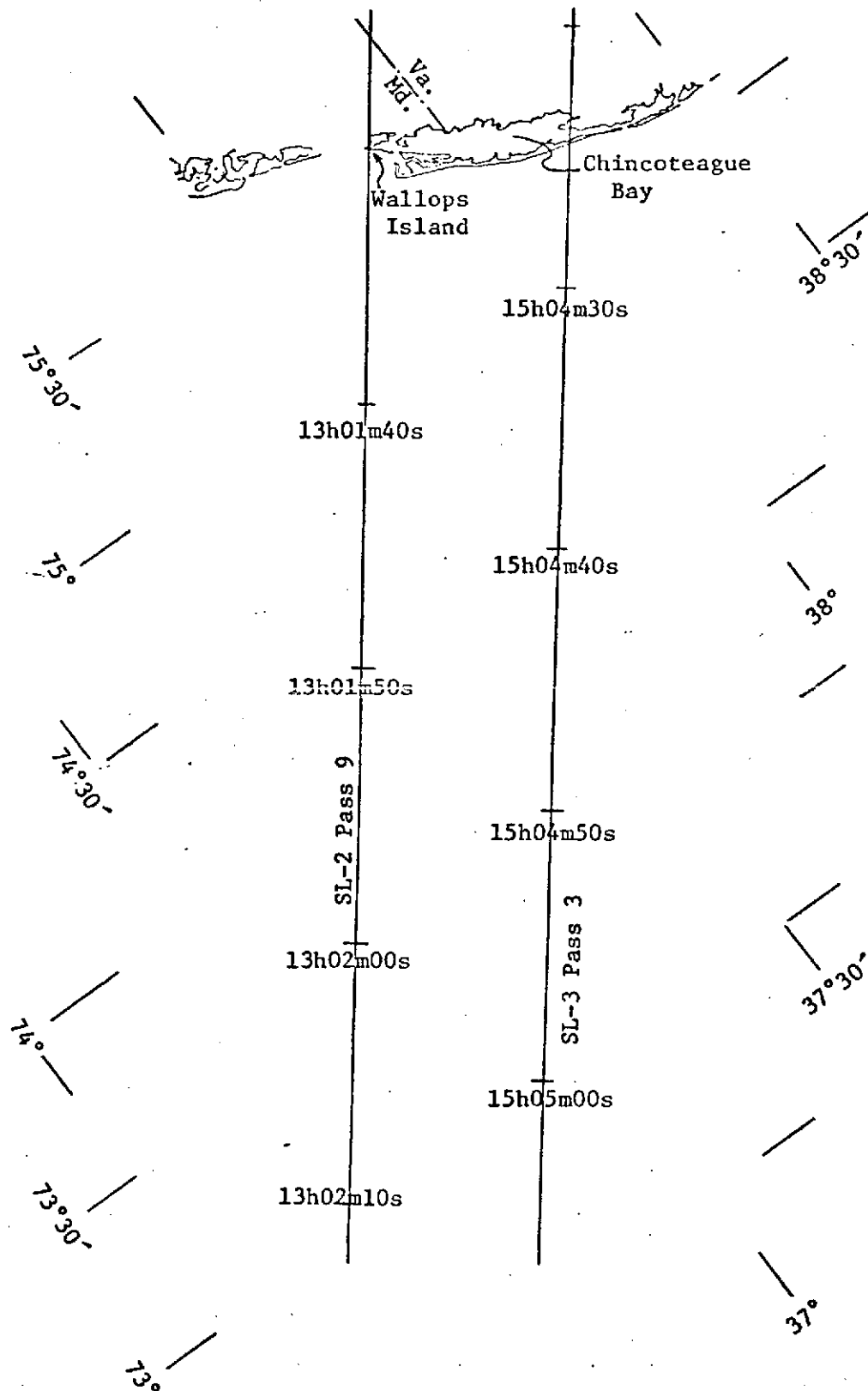


Figure 2-1. Ground Traces for SL-2 Pass 9 and SL-3 Pass 3.

trace was almost a reproduction of that of Pass #6 from SL-3. This pair of passes, along with Pass #9 of SL-2 and Pass #3 of SL-3, offered a good opportunity to compare topographic observations of the Gulf Stream at approximately the same location -- although the SL-4/SL-3 pair were separated in time by over 5 months and the SL-2/SL-3 combination by about 2 months.

Because this selection process resulted in only two reasonably hopeful altimeter data takes for the purpose of this study, i.e., EREP #9 from SL-2 and EREP #3 from SL-3, an attempt was made to determine whether another strong ocean current such as the Kuroshio, Agulhus, Cape Horn or East Australia, had been over-flown in more or better altimeter takes, but coverage for the Gulf Stream was found to be far better than for any other current. Figure 2-2 from Reference 15, shows currents in the world ocean in northern winter.

Due to the small number of promising passes and the limited time and funds available for reduction of data, it was decided that altimeter altitude data for only four passes of the eight initially selected would be filtered in hopes of producing indications of Gulf Stream topography. These were: EREP #9 from SL-2, EREP #3 and #6 from SL-3, and EREP #32 from SL-4. As is indicated later in Section 4, only two of these four yielded useful results. No data was identified as suitable for analysis from SL-4, and the data from Pass #6, SL-3, was anomalous in that it was much noisier than any other data observed.

Consequently, the analysis was limited to only Pass #9 from SL-2 and Pass #3 from SL-3.

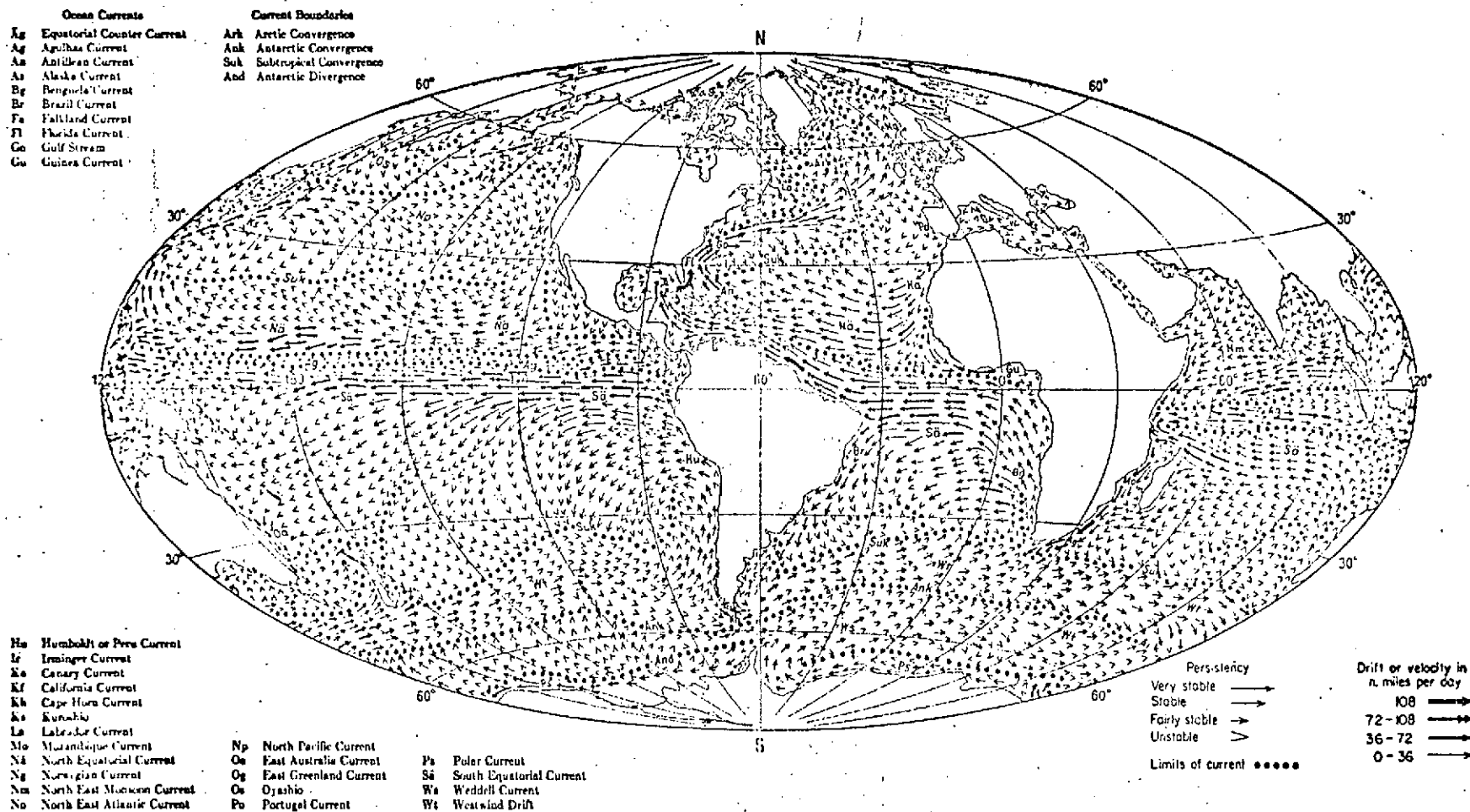


Figure 2-2. Currents at the Surface of the World Ocean in Northern Winter.

### 3. IR AND VISUAL DATA

In recent years, satellite radiometers have produced excellent images of ocean current boundaries in cloud-free conditions. The Very High Resolution Radiometer carried on NOAA-2 is a source of both visual (0.6 to 0.7 $\mu$ m wavelength region) and infrared (10.5 to 12.5 $\mu$ m wavelength) information on the earth's surface, with a resolution of about 1 kilometer in each case. This IR resolution has made possible the observation of coastal surface temperatures in fine detail. Figure 3-1 is a composite from the NOAA-2 VHRR IR channel, on 24 and 25 March, 1973, showing the northern portion of the Gulf Stream in spectacular detail (the darker regions are the warmer, western boundaries of the stream). Although this picture shows a very complex western boundary shape (which is not really atypical), it does illustrate why it was desirable in this study to emphasize the Gulf Stream north of Cape Hatteras. The turn to the east and resulting displacement from the Continental Shelf is very typical, and this offers the chance to observe the stream in "free-water" without effects of shore or bottom on either the stream or the water surface.

A visit was made to the office of the Environmental Satellite Services of NOAA, to determine what IR/visual data was available from NOAA-2 on the Skylab passes previously selected. Table 3-1 shows the results of that trip. (It should be noted that this trip was made and the IR data selected before it was discovered that only two of the altimeter data take passes were useful for analysis.)

During the periods in June of 1973 when the S-193 altimeter was overflying the Gulf Stream, the entire Middle Atlantic coastal region was obscured by extensive cloud cover which prevented any IR or visual observation of the Gulf Stream, except for EREP Pass #9 on 12 June. Figure 3-2 is a NOAA-produced chart of the Gulf Stream for that date. The western boundary of the stream is well-defined, although its shape is again somewhat complex.

Images for the two passes in SL-3 were also partially obscured by cloud cover and the Gulf Stream IR signature registration was poor. These two passes occurred on 5 and 9 August of 1973. Figures 3-3 and 3-4 are NOAA-produced charts showing the Gulf Stream on 24 July and 27-30 August, 1973, respectively. Although neither of these show the Gulf Stream off Cape Hatteras (thus leaving exact Gulf Stream location for Pass number 6 in question), they both show

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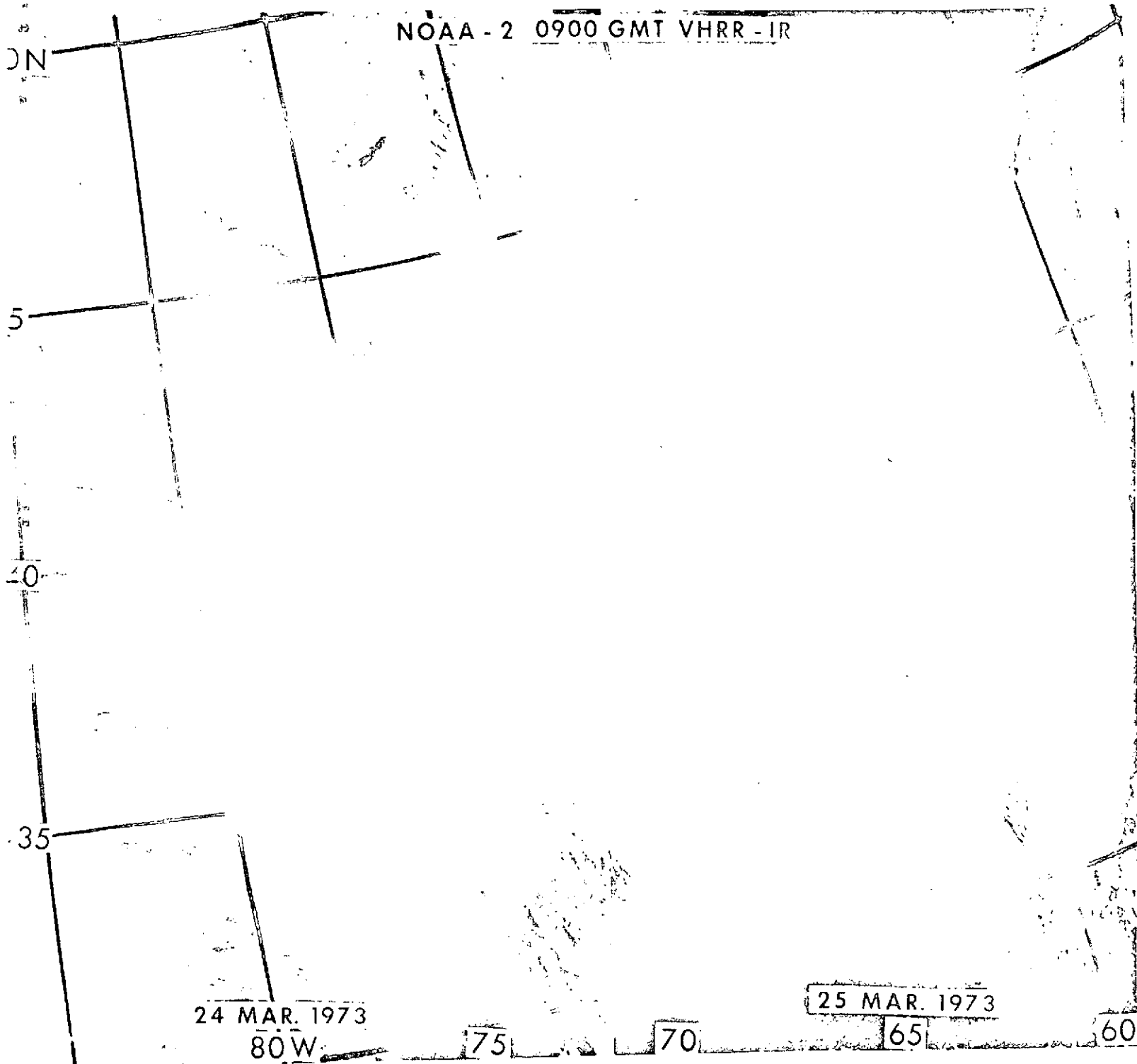


Figure 3-1 - VHRR IR Image of Gulf Stream  
24, 25 March, 1973

TABLE 3-1

IR/VISUAL DATA FROM NOAA-2 ON SKYLAB PASSES SELECTED

SL-2

<u>EREP PASS NO.</u>	<u>DATE</u>	<u>IR/VISUAL COVERAGE</u>
4	6-4-73	Cloud Cover
9	6-12-73	Good IR Data on NOAA Analysis Chart

SL-3

3	8-5-73	Partial Cloud Cover Poor IR Image
6	8-9-73	Partial Cloud Cover, Poor IR Image

SL-4

4	11-30-73	Good IR and Visual Images
30	1-18-74	Good IR and Visual Images on 1-17
32	1-20-74	Cloud Cover on 1-19, Good Data on 1-21
37	1-22-74	Poor Data, Some Cloud Contamination

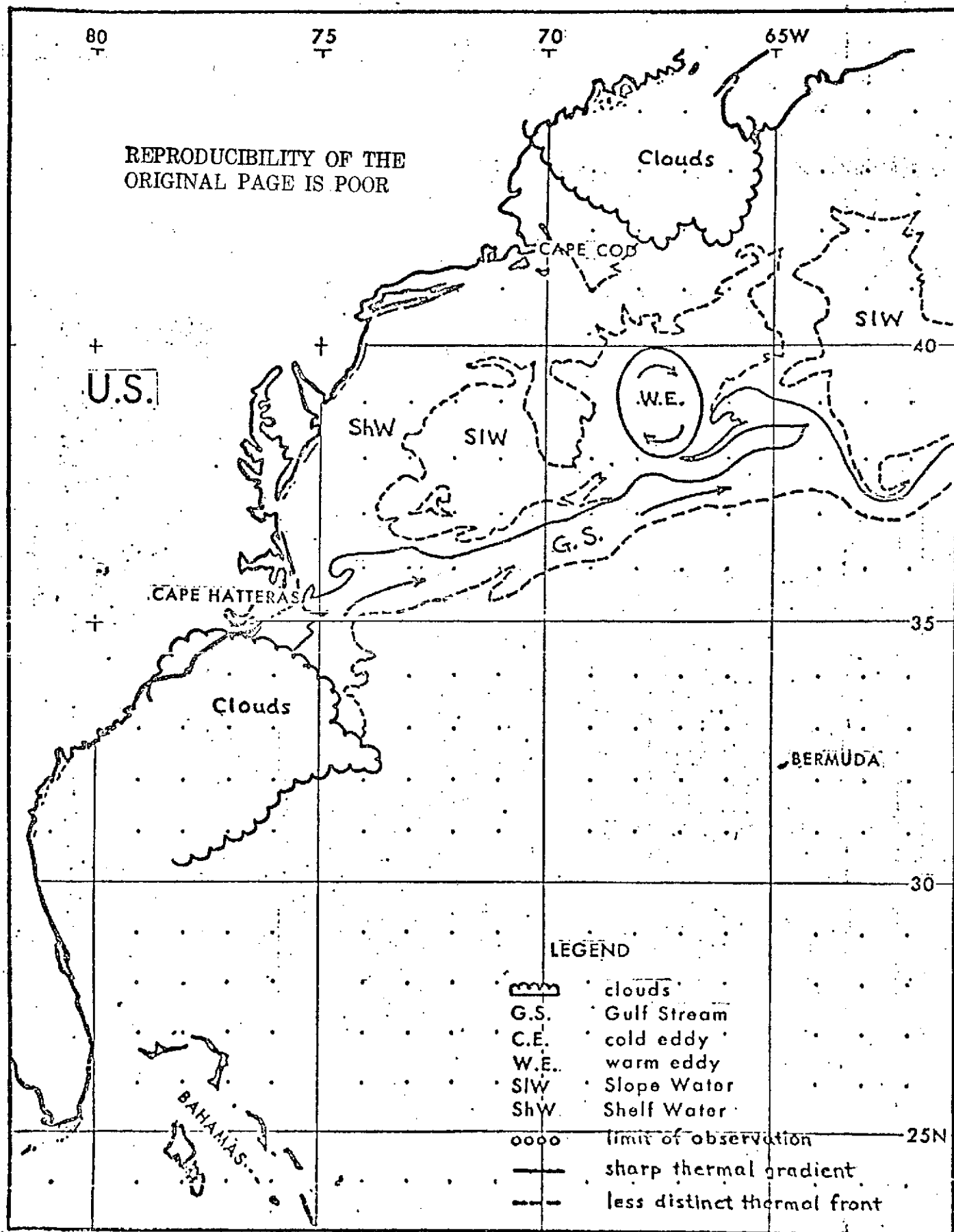


Figure 3-2. Experimental Gulf Stream Analysis,  
NOAA-2 Satellite Thermal IR Observed 11-12 June 1973

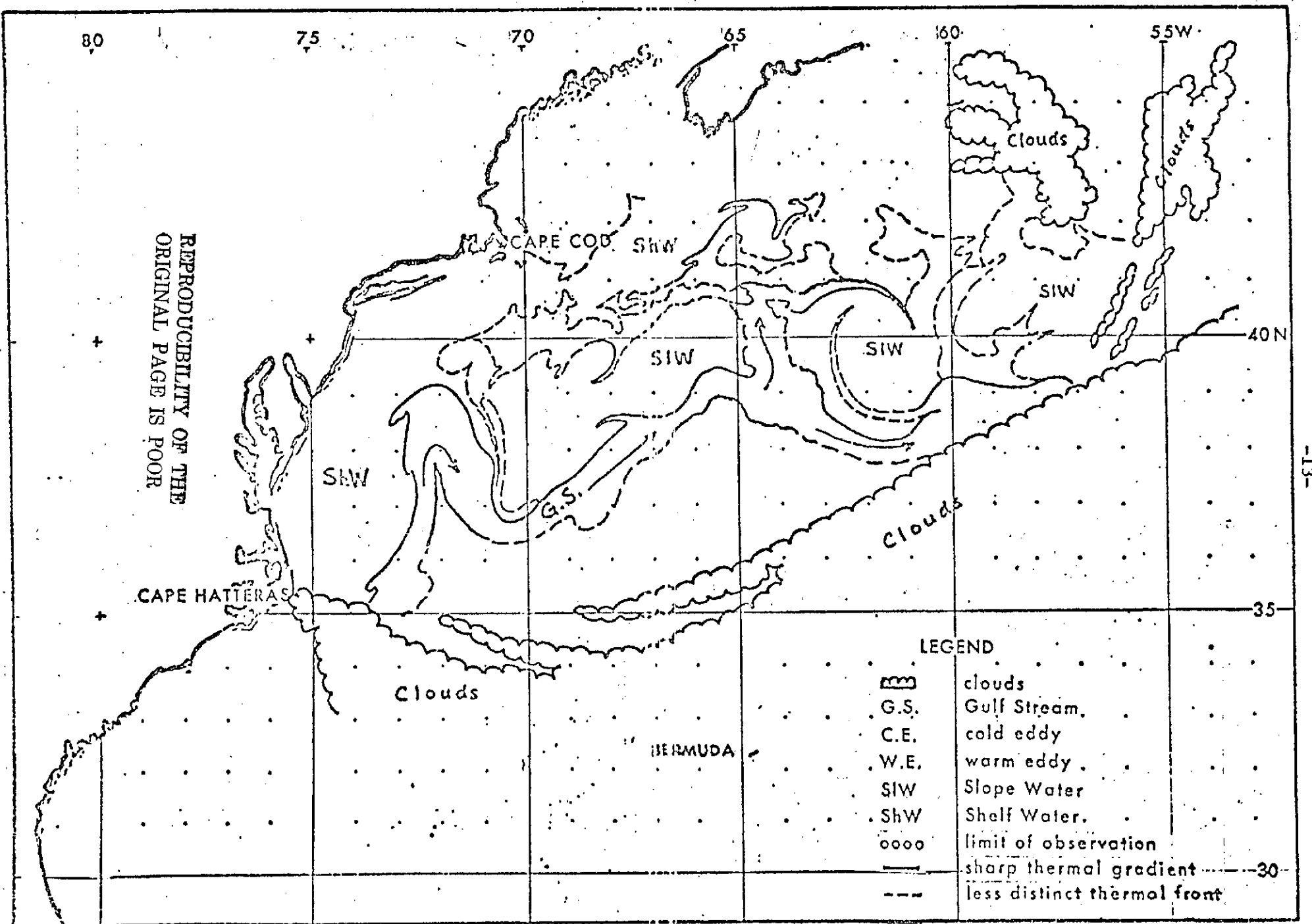


Figure 3-3. Experimental Gulf Stream Analysis, NOAA-2 Satellite Thermal IR Observed 24 July 1973



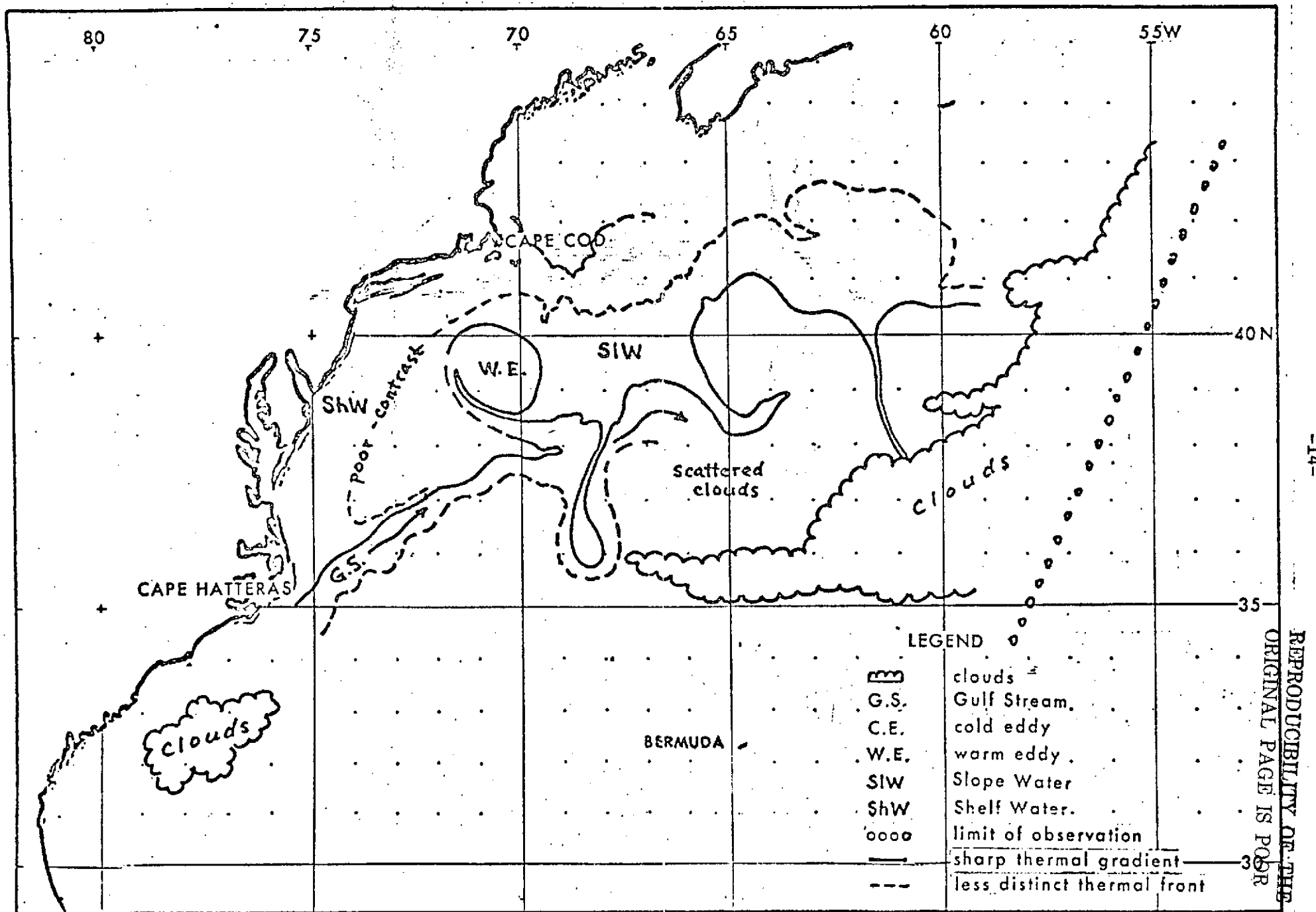


Figure 3-4. Experimental Gulf Stream Analysis, NOAA-2 Satellite Thermal IR Observed 27-30 August 1973.

stream location for the Pass 3 ground trace. The chart for 24 July is felt to be more applicable for the Pass 3 overflight because it is closest to the date of Pass 3 (5 August). The ground trace is seen to intercept the western edge of the Gulf Stream at about  $36^{\circ} 45'N$ ,  $72^{\circ} 50'W$ .

Some good IR data was taken on the passes selected for SL-4. Figure 3-5 is a chart of the Gulf Stream for EREP Pass #32. The western boundary of the Gulf Stream is seen to be very complex here, and, depending on exactly where the ground trace occurred, could result in as many as three western boundary crossings. Figure 3-6 is an IR image taken the night following the day of the EREP pass. Although thermal gradients have lessened due to the night cooling, the Gulf Stream can still be distinguished until it disappears under a line of clouds as it turns eastward north of Cape Hatteras.

Thus, there is reasonably good infrared data on the Gulf Stream boundary in the two cases finally analyzed: EREP Pass #9 on SL-2 and EREP Pass #3 on SL-3.

An interesting statistic observed in this selection process and reported by others as well (Reference 10) is that useful IR/visual data appears to occur in approximately one-third of the opportunities for observation. This appears to be attributable primarily to cloud problems.

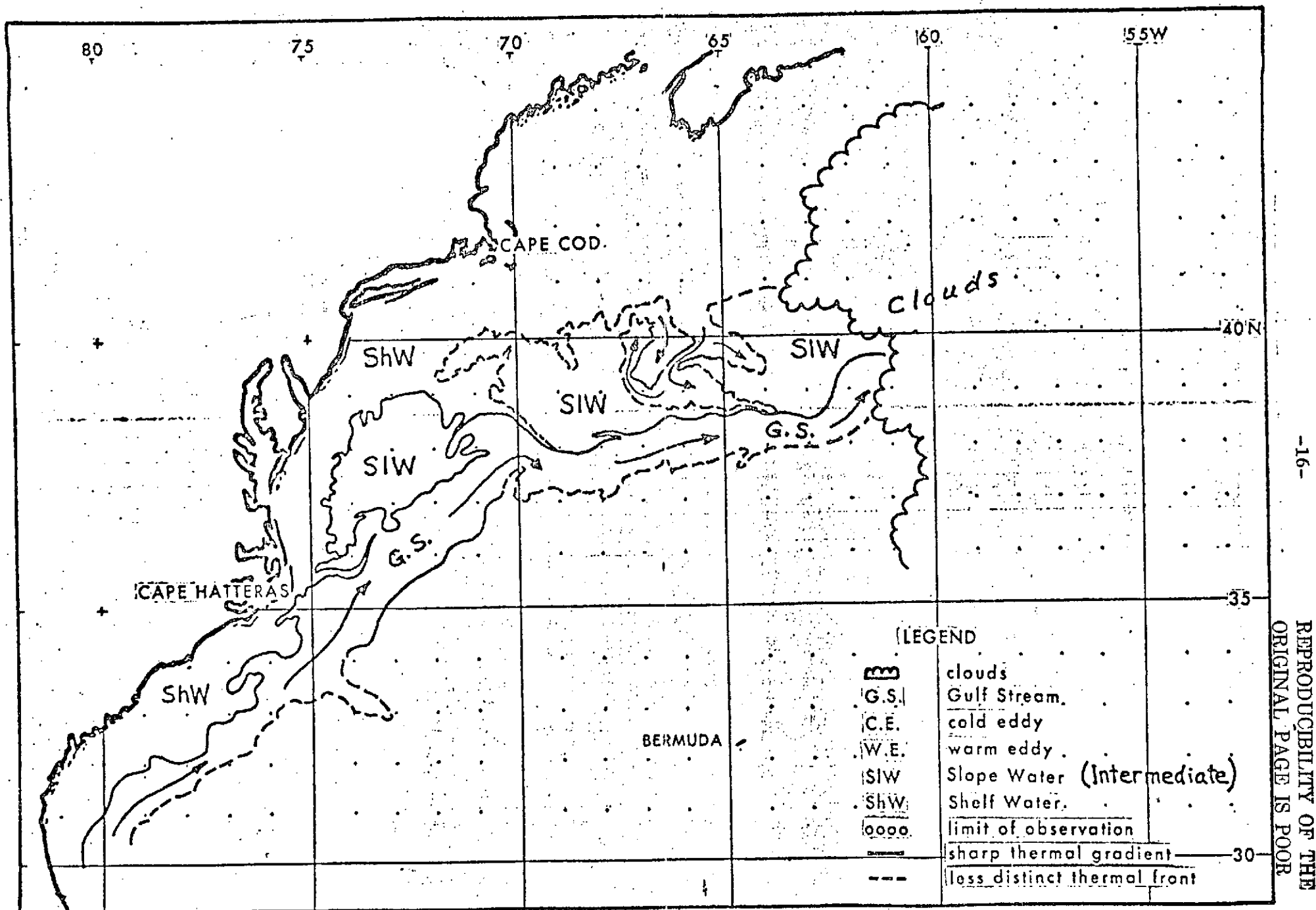


Figure 3-5. Experimental Gulf Stream Analysis, NOAA-2 Satellite Thermal IR Observed 21-22 January 1974.

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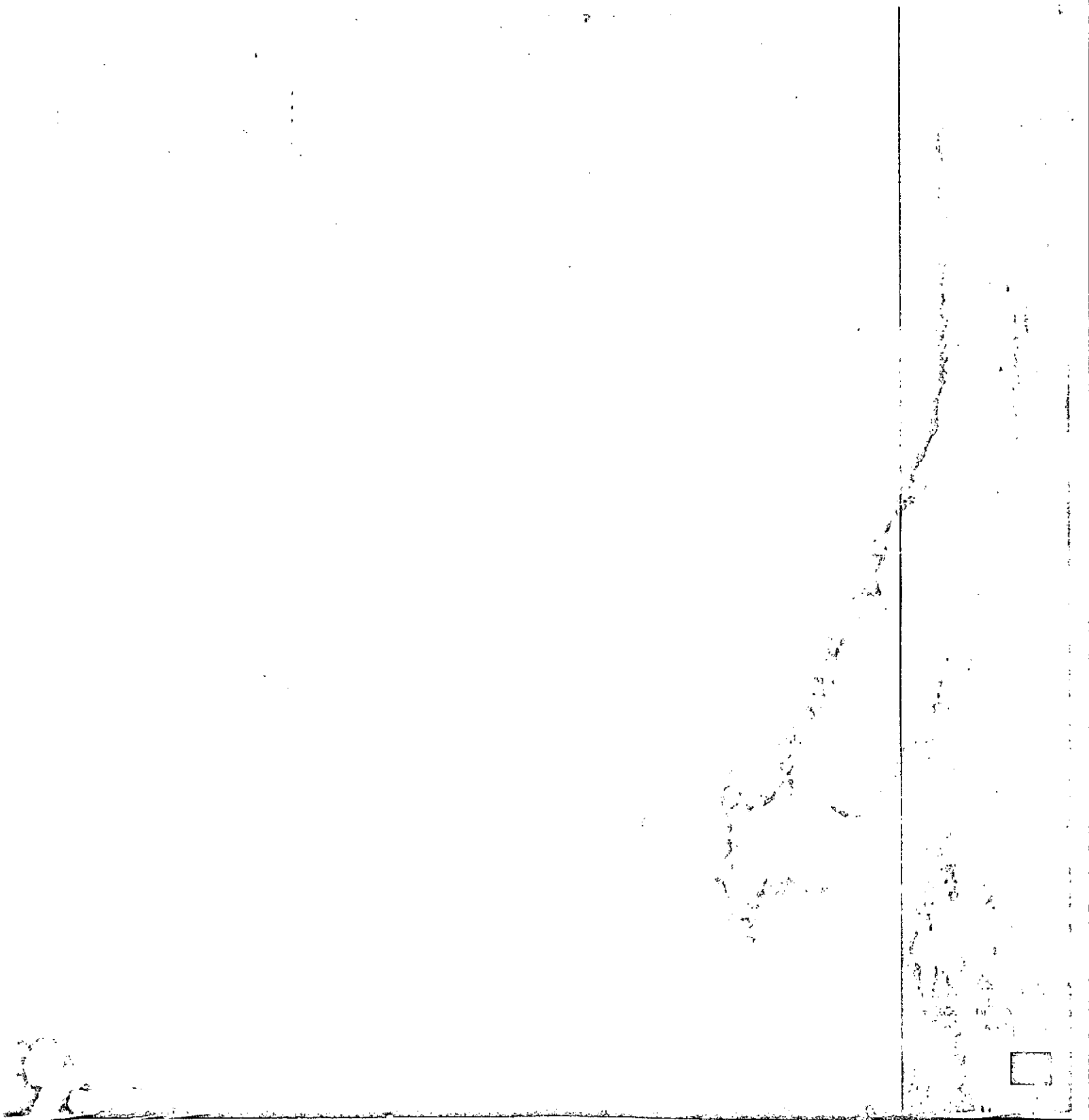


Figure 3-6 - VHRR IR Image of Gulf Stream  
21 January, 1974

#### 4. ANALYSIS OF ALTIMETER DATA

For the altimeter data-take passes selected for study, data was obtained over a time period bracketing the expected position of the Gulf Stream (the western edge location was used since the major topographical feature should occur near the western wall of the current).

The data obtained for analysis consisted of tabulations of both raw residuals and residuals resulting from the fitting of estimates of the satellite orbit from tracking system data) to altimeter altitude measurement data. These orbit-corrected values are produced by the GEODYN computer program used by Wallops Flight Center.

The first data processing technique to be discussed consisted of three steps: (1) the raw residuals were plotted and examined for data drop-outs, anomalies and other obvious features; (2) interpolation routines were then used for filling-in missing points and (3) a finite impulse response filter\* was applied to the residuals, and the results examined for evidence of Gulf Stream topography. Figure 4-1 shows the results obtained when this filter was applied to SL-2 Pass 9 residuals. Figure 4-2 shows the results from SL-3 Pass 3. The results from SL-3 Pass 6 were so noisy, even after filtering, that further treatment of data from that pass was not considered worthwhile.

It had been hoped that the filtered data from SL-3 Pass 3 and SL-2 Pass 9 would be similar, since the ground tracks for these two almost overlap and ground truth data indicated almost the same Gulf Stream location for the two, but, as Figures 4-1 and 4-2 show, the results are not comparable. The five meter change in altitude over a period of 12 seconds in SL-3 Pass 3 data is not to be found in the SL-2 Pass 9 data, even though the data span in Figure 4-2 should correspond to an equal data span near the center of Figure 4-1. It may be that the apparent feature in Figure 4-2 is due to the antenna tilt occurring in sub-mode 1 which was energized just prior to the time span shown, or to other basic differences between Modes 1 and 5. It is

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\*The derivation of this filter is given in Appendix B. Its optimality is based on known noise properties of the S-193 instrument. From this standpoint it represents the highest spatial resolution filter justifiable for use with the S-193 data.

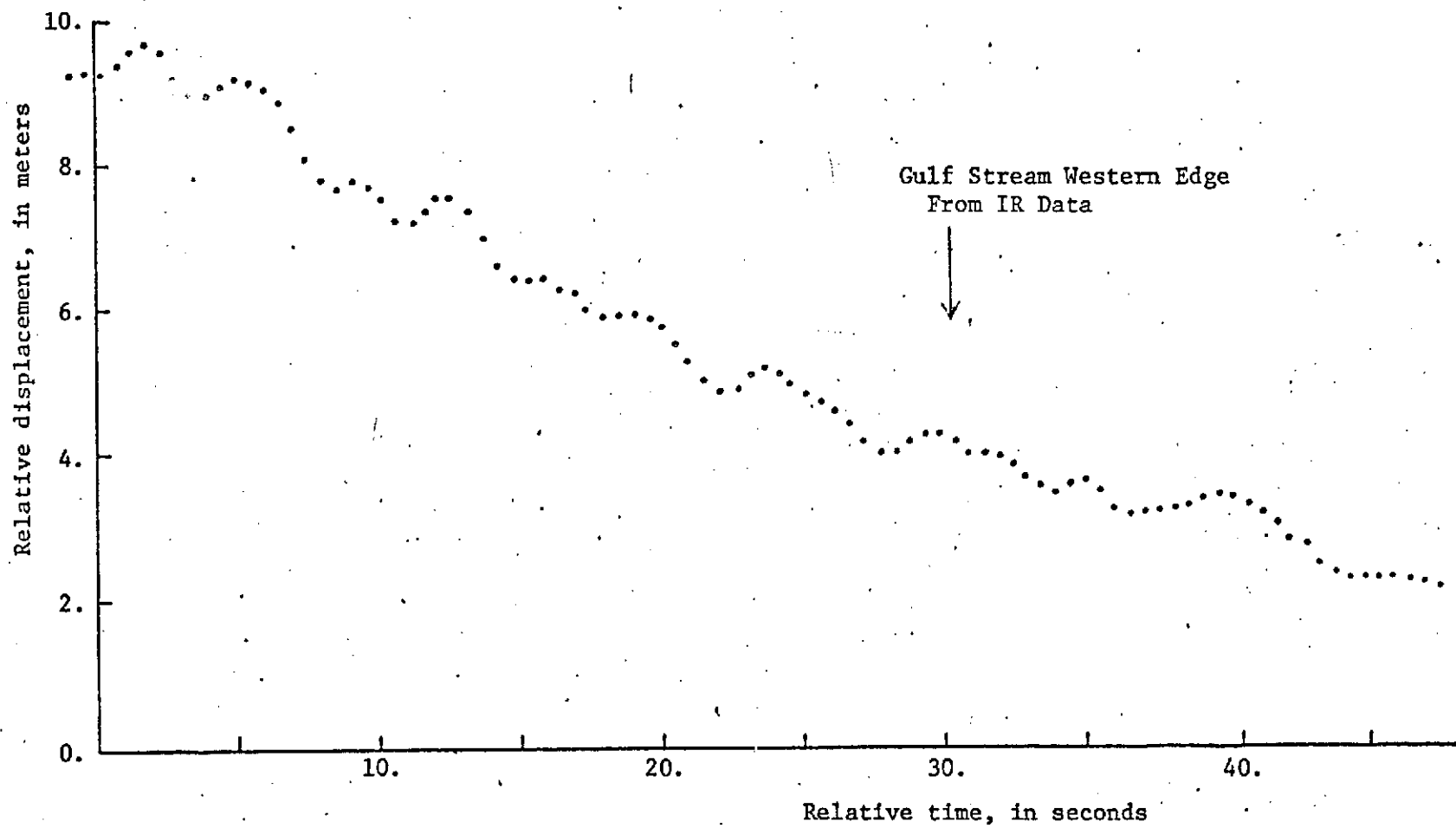


Figure 4-1. Filtered Residuals from SL-2 Pass 9.

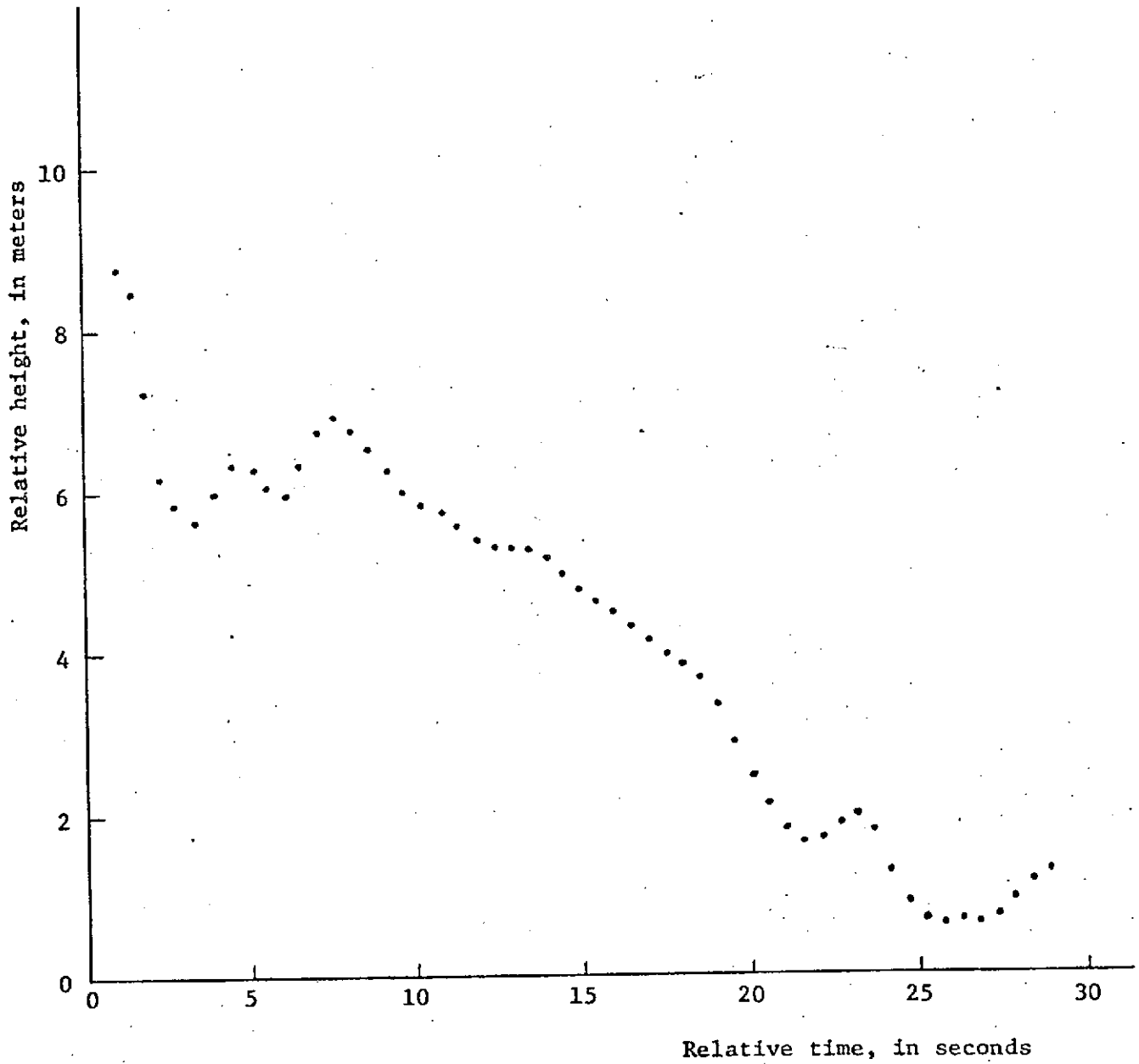


Figure 4-2. Filtered Residuals From SL-3 Pass 3.

obvious that this is an anomaly in any case, and its resolution was not possible during this study.

The filtered data from SL-2 Pass 9 (Figure 4-1) from a noise standpoint represents the highest quality altimeter data encountered in this study. The trend-line evident in these data is very close to the Marsh-Vincent geoid (see Figure 4-3).

The only tentative conclusion which can be reached, since no overlapping data span is available for comparison, is that some of the noise-like variation in Figure 4-1 may be due to Gulf Stream topography.

In the second form of data processing used the edited altimeter data for Pass 9 were least-square fitted to a low-order polynomial and the smoothed residuals were studied. In effect, the polynomial served to remove the long wavelength geoidal trend shown in Figure 4-1. If large, short-wavelength geoidal features were thought to be present in the data, such a procedure would not be very useful.\* As a further assessment of the technique, second through fifth order polynomials were used and variance of the residuals were found to be essentially equal. This result supports the concave or parabolic nature of the trend-line suggested by the data shown in Figure 4-3.

Figure 4-4 shows the result of this data processing procedure; residuals of the 4th order polynomial were smoothed using an 8 second moving-window filter. This degree of smoothing was used to reduce the random measurement errors\*\* to the greatest possible extent, without serious attenuation of any possible Gulf Stream feature. The most interesting event in Figure 4-4 is the ~55 cm positive excursion which occurs ~220 nmi off shore; however, the rms value of the residuals (~20 cm) limits the statistical significance of any single event in the results.

Figure 4-5 shows a possible model of the altimeter response to the Gulf Stream [23]; it represents the calculated perturbation in ocean surface topography, based on measured Gulf Stream velocity profiles. The computed Gulf Stream feature in Figure 4-5 and the largest deflection observed in

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\*This appears to be the case for altimeter data recorded off the coast of South Carolina, cf. Figure 15 of [26].

\*\*Based on S-193 system information the expected tracking jitter is ~125 cm rms in this mode. Using a tracker bandwidth of 3.3 Hz and 8 sec. smoothing, the anticipated residual noise level was ~18 cm rms.



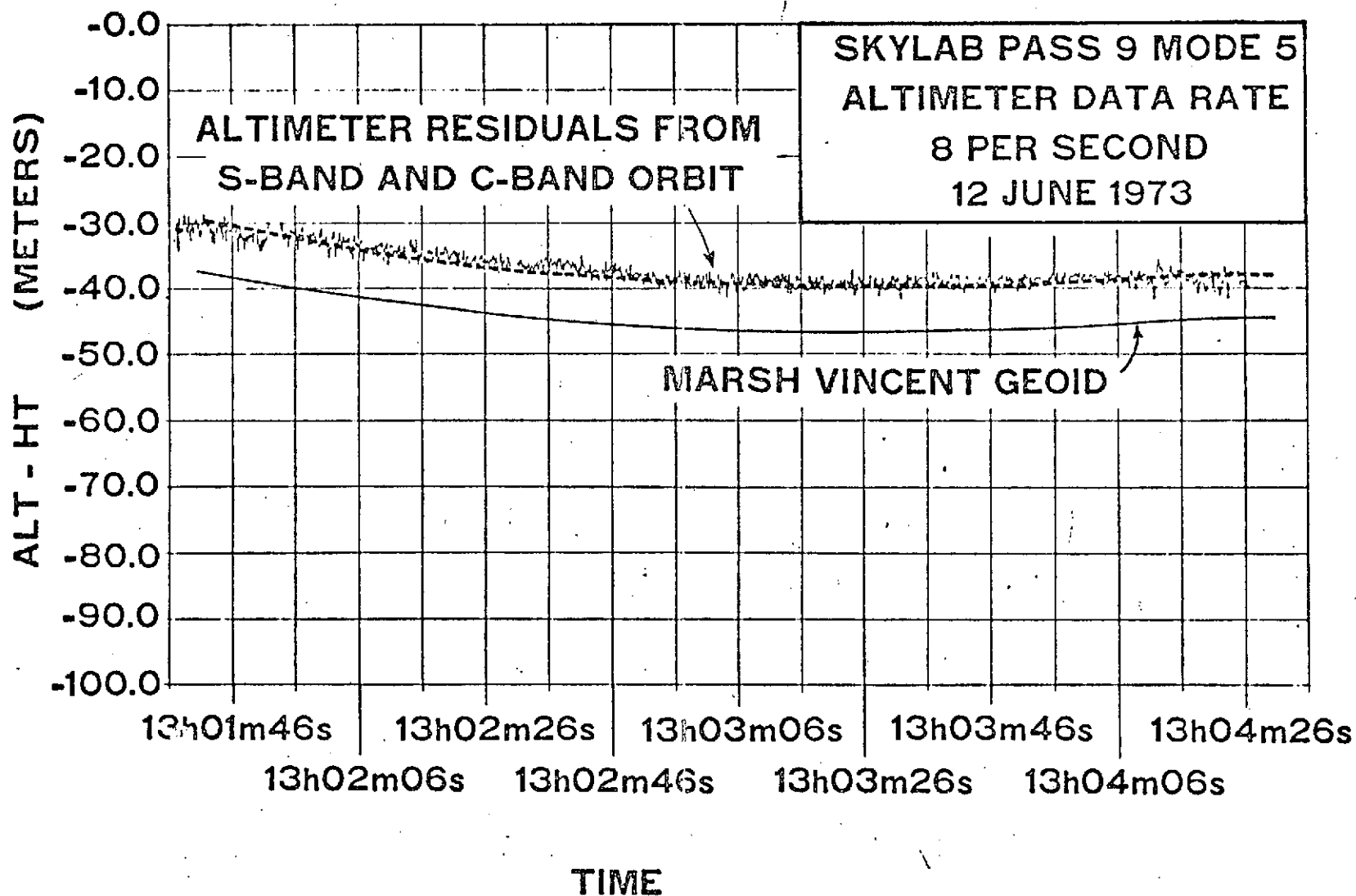


Figure 4-3. Altimeter Residuals and Marsh-Vincent Geoid for SL-2 Pass 9.

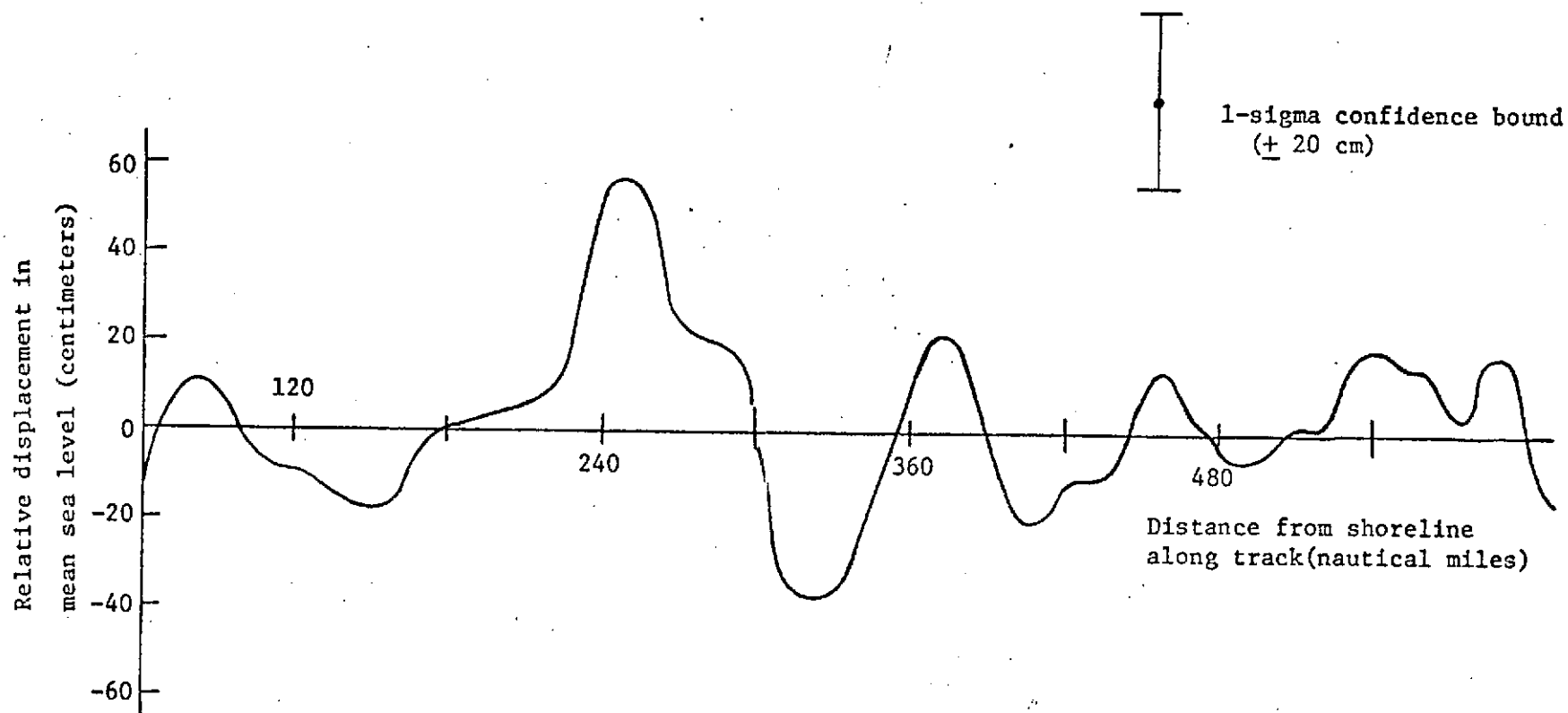


Figure 4-4. Altimeter Residuals Using a 4th Order Polynomial and 8 Second Smoothing

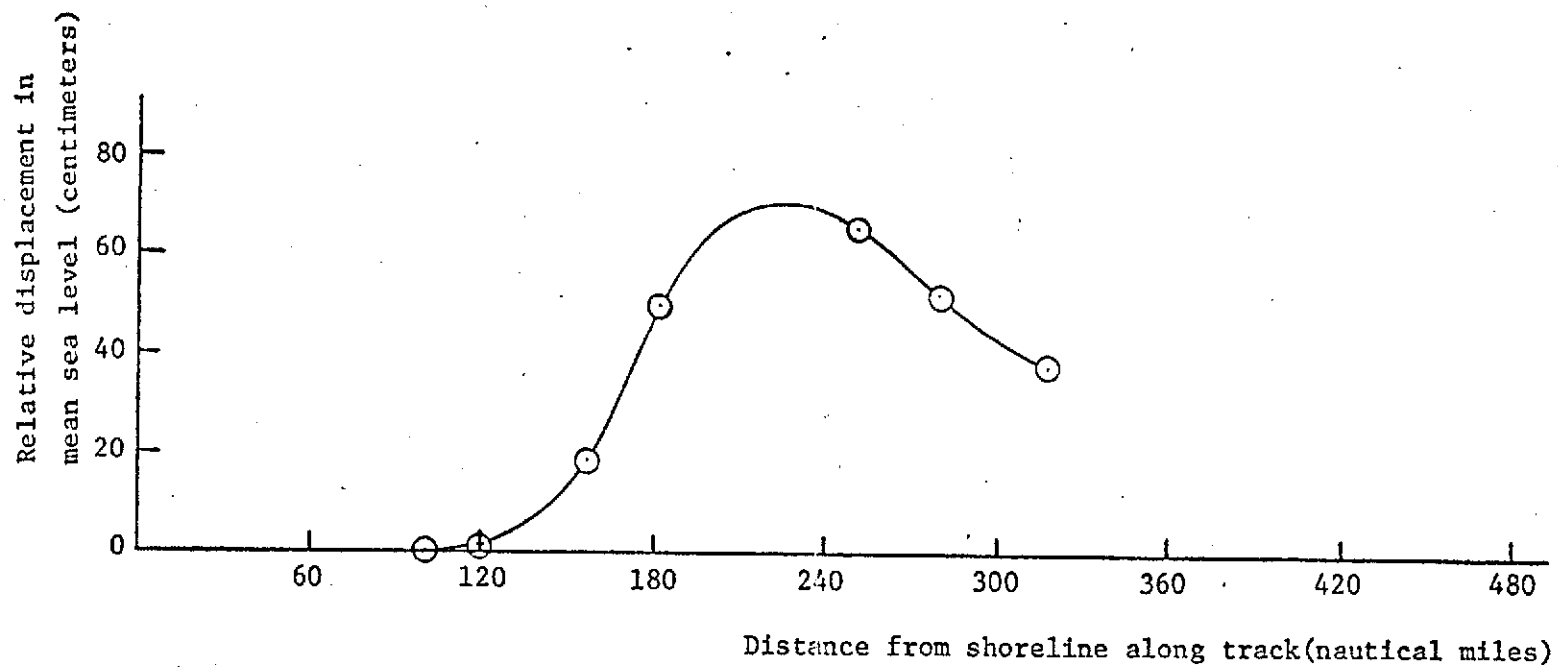


Figure 4-5. Calculated Gulf Stream Surface Topography From [23]

Figure 4-4 occur at roughly the same geographic location - which is >50 nmi southeast of the eastern boundary seen in the IR images. Much more data is needed before firm conclusions can be made; however, it appears that there may be a sizeable displacement between the surface thermal discontinuity and the altimeter-inferred mass transport.

In closing this section we wish to emphasize that the freedom from geoidal fine-scale effects in Pass 9 allowed us to make use of this second method of data processing. In general, one would wish to obtain a number of repetitive passes and then attempt to separately catalog permanent geoid effects and time-varying effects. Areas south of Pass 9 appear to be geodetically more complex.

## 5. COMPARISON OF IR AND ALTIMETER DATA

Since features attributable to Gulf Stream effects of sufficient detail and statistical significance were not present in the altimeter data, it was not possible to compare the altimeter-observed Gulf Stream with the IR radiometer-observed Gulf Stream.

A close examination of Figures 3-2, 3-3 and 3-4, which apply to Gulf Stream conditions in June, July and August of 1973, respectively, reveals that the selection of satellite passes over the Gulf Stream during this time period was probably unfortunate, as these figures suggest that the Gulf Stream was undergoing an anomalous condition during that time. In the geographic region of the satellite ground track over the Stream, which is in the vicinity of the point at  $36^{\circ}\text{N}$ ,  $73^{\circ}\text{W}$ , it can be seen that a bulge is developing in the western boundary of the Stream in Figure 3-2, the bulge has transformed into a large bend north of the point in Figure 3-3, and an eddy has been formed in Figure 3-4. The topographic conditions accompanying this behavior are not known, but it is reasonable to assume that the warm water boundary configuration, which is the characteristic depicted in these figures, may have less correlation with the configuration of maximum current flow -- and therefore maximum expected topographical disturbance -- than would normally be the case when an eddy formation is not taking place. The SL-2 Pass 9 overflight took place on 12 June, which is the date associated with Figure 3-2 and the beginning of the Stream boundary distortion. SL-3 Pass 3 occurred on 5 August, which is twelve days after the condition shown in Figure 3-3, but twenty-two days before the return to normal shown in Figure 3-4. It is therefore entirely possible that the Gulf Stream current was so distorted when the two passes occurred that the topographic characteristic predicted from normal current flow did not exist.

This circumstance casts even the final two passes available for analysis in a questionable light, so that the objective of observing Gulf Stream topography in Skylab altimeter data is rendered fruitless. Even though the result of this portion of the study is inconclusive however, the lessons learned in attempting the analysis are valuable and will be useful to those pursuing similar objectives in GEOS-C and later programs.

It is worthwhile to note that indications of Gulf Stream locations for the passes considered here, where there was data available from the NOAA-2

satellite IR radiometer and from the Coast Guard aircraft IR radiometer used in the ART (Airborne Radiation Thermometer) program, generally were in good agreement.

In conducting this study, it was assumed that the Gulf Stream current caused an observable water surface perturbation similar to that already shown in Figure 4-5 which is a preliminary result from a study being conducted by N. Huang *et al.*, (Reference 23) where oceanographic parameters are used in a theoretical model to calculate surface elevation changes due to the current. The data used to produce the calculated result in Figure 4-5 was collected over a period of six days, which is typical of the minimum time period usually required to gather the necessary oceanographic measurements from measurement stations distributed over the geographical area of interest.

A second assumption implicit in the study conducted was that the Gulf Stream-caused surface topography would be accompanied by a thermal characteristic at the surface which could be observed by airborne radiometers. Thus IR images showing warm-water contours such as that of Figure 3-1, normally interpreted to be caused by the western boundary of the Gulf Stream, could be used to define the expected location of the surface topographic perturbation due to the Gulf Stream.

A simple truth is that, although these two assumptions are justifiable with a certain amount of logic and scientific reasoning, they have not yet been supported by experimental evidence. The results of this study might have served this purpose, but the fact that the study produced no corroborative experimental data does not mean that the assumptions are invalid. Even if positive results had been obtained, the sparsity of useful data with which to work would have reduced the statistical significance of the results.

There are two important questions bearing on these assumptions however, the answers to which would provide much better insight as to how to interpret experimental results as well as how to optimize the design of future experiments. These are: (1) what is the short-term time variability of the surface topography due to the Gulf Stream?, and (2) what is the relationship between current-caused surface topography and surface temperature; further, what do either or both of these imply about the at-depth location of the Gulf Stream?

The answer to the first of these probably can only be supplied by satellite radar altimetry, but it will require at the minimum several passes over

the same cut across the surface of the Gulf Stream spaced as closely in time as possible and under the same altimeter operating and surface environmental conditions (or several satellites with radar altimeters passing over the same Gulf Stream surface cut in short-term sequence - a desirable but highly impractical alternative). The crux of this question is the validity of the correlation of the several seconds of radar altimeter data from a single pass over the Gulf Stream with the several days of oceanographic station measurement data from which Gulf Stream topography is inferred.

The second question has been treated in part by Hansen and Maul (Reference 17) and others, but direct experimental evidence must await the time when simultaneous measurements from a satellite-mounted radiometer and radar altimeter of both surface temperature and topography are available, and accompanying experimental data has been produced showing the short-term surface topography/at-depth current location relationship.

There is still another indirect observable which can be obtained from satellite radar altimetry to indicate Gulf Stream surface effect; this is a change in surface wave height probability density which has been predicted theoretically and verified experimentally in the laboratory (Reference 24), but has not yet been observed in actual radar altimeter measurements, although aircraft-mounted sensor experiments are presently being conducted for this purpose. This effect could be cross-checked against observations of changes in optical reflection characteristics through visual images of sun-glint from the Gulf Stream surface (Reference 7).

## 6. DISCUSSION OF PROBLEMS ENCOUNTERED

Aside from several basic problems which directly affect the outcome of this study, there are some fundamentals about which very little is known that need to be understood and resolved before results from a task such as this will have much meaning or, more important, before satellite altimetry will reach its full potential as a source of ocean surface topographical information.

The problems which affected the results of this study and about which nothing can be done until GEOS-C is aloft are:

- (1) There were too few altimeter data takes on the "free" Gulf Stream to enable any confidence to be established in the results obtained,
- (2) Since (1) is true, it is obvious that there were also not enough repeated passes to enable confidence to be gained in repeatability of results - or understanding of non-repeatability,
- (3) The noise level in altitude tracking was too close to the expected variation in altitude due to ocean surface topography, making (1) and (2) even more critical.

The fundamentals which need better understanding and resolution are:

- (a) There is too much uncertainty and disagreement between versions of the geoid to be able to confidently attribute altimeter topography measurement results to either geoid or dynamic topography,
- (b) There is considerable uncertainty as to the expected shape of the Gulf Stream surface topography, making the choice of an optimum filter for extraction of the topographic characteristic difficult,
- (c) The western boundary of the Gulf Stream appears from IR images to be typically complex in shape, with curls and fingers and fuzzy definition, so that the corresponding physical picture may be equally complex in real time -- thus, the characteristic expected, whatever its general shape is predicted to be, may not exist in results from a single pass,
- (d) Although probably not of the same order of importance as the above factors, there is a lack of quantitative information on the accuracy with which an observed thermal characteristic represents the physical location of the Gulf Stream -- particularly the physical location of the current-induced topography.



For the purpose of the present study, these problems have all been ignored out of necessity due to time and resources available, but it is important that they be identified and discussed, so that the results of the study can be placed in proper context.

It is felt that the three basic problems affecting the results of the study are self-evident and require no further discussion; they all relate to the statistical validity of results obtained. They have their solutions in better data acquisition plans so that sufficient data can be available to establish the required confidence levels for future results to be obtained.

The more fundamental problem areas need some additional explanation in order to better illustrate the severity of their effects on this type of investigation:

(a) Geoid Uncertainty

As Greenwood et al. (Reference 1) have pointed out, currently available geoid estimates differ from each other to the extent that the slopes produced when two geoids are differenced are two orders of magnitude larger than those produced by ocean currents. Figure 6-1, from Reference 1 shows a plot of the Kaula geoid minus the Guier-Newton geoid. It is interesting to compare this plot with that shown in Figure 6-2, which is a superposition of the Guier-Newton geoid and Defant's estimate of current-caused sea-surface topography (from Reference 2). The Defant topographic estimate is shown in Figure 6-3.

Table 6-1, also from Reference 1, further illustrates the variation between various geoid estimates by giving the locations and heights of several major geoidal features according to several estimates of the geoid. Figure 6-4, shows the relative locations of these feature estimates. These are lower frequency features. It is well known that much uncertainty exists in the higher-frequency, smaller spatial extent features -- in fact, satellite altimeters are regarded as a great potential source of this higher-frequency geoidal information. The problem which is going to be difficult to resolve here is the separation of small-scale geoidal feature characteristics from dynamic topographic characteristics which have similar effects in satellite altimeter data.

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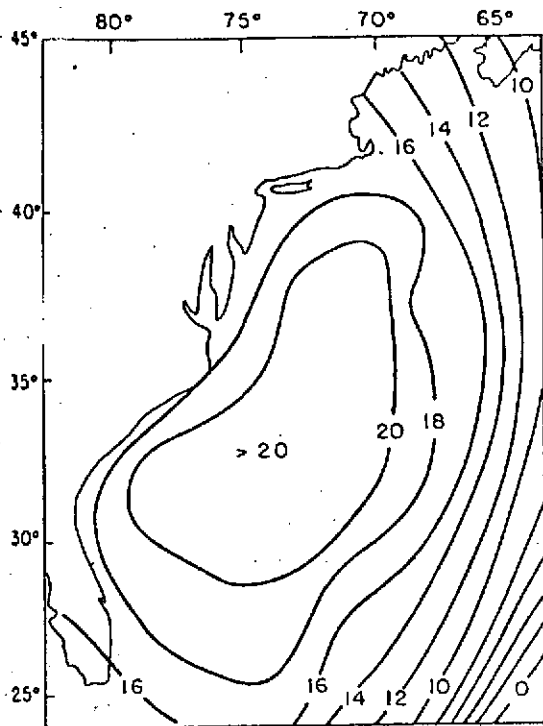


Fig. 6-1. Kaula geoid minus Guier-Newton geoid, in meters.

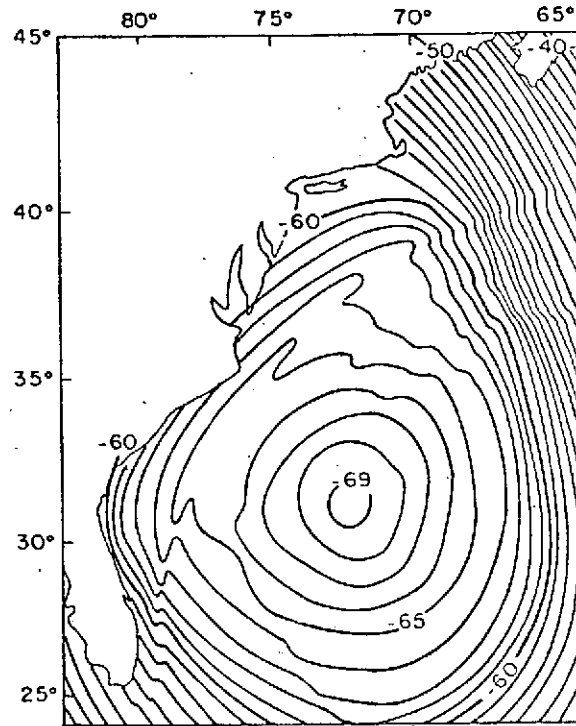


Fig. 6-2. Superposition of Guier-Newton geoid and sea-surface topography for Gulf Stream region.

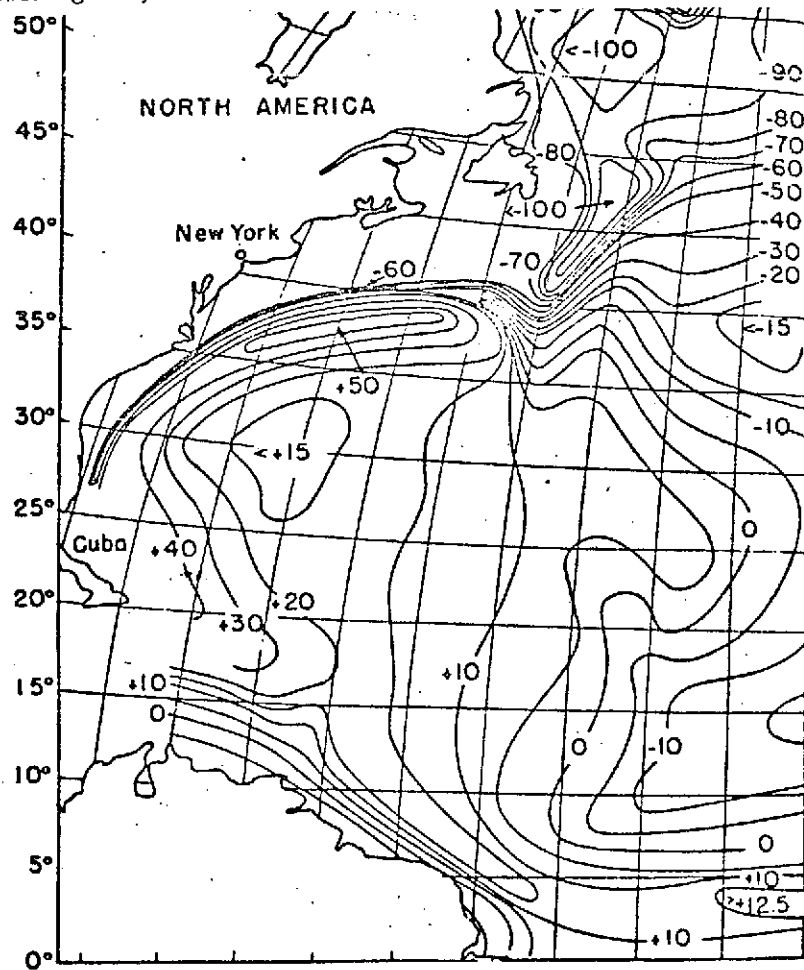


Fig. 6-3. Dynamic topography of the western North Atlantic, according to Defant (1941). Contours are labeled in centimeters.

Location	Coordinate	Source				
		Izak	Gaposchkin	Kaula	Guier and Newton	Anderle
Near North Atlantic	Lat	50°N	40°N	50°N	55°N	55°N
	Long	20°W	15°W	0°	5°W	15°W
	Height,m	43	54	62	67	65
Antarctic Ocean	Lat	50°S	50°S	50°S	50°S	45°S
	Long	45°E	50°E	50°E	50°E	15°E
	Height,m	49	49	48	39	45
Western Pacific(near Japan)	Lat	10°S	10°S	5°S	25°N	5°N
	Long	155°E	155°E	145°E	140°E	140°E
	Height,m	63	69	67	60	75
Indian Ocean	Lat	10°N	5°N	0°	5°N	10°N
	Long	75°E	75°E	75°E	75°E	75°E
	Height,m	-73	-92	-79	-77	-95
East Pacific	Lat	20°N	35°N	30°N	25°N	15°N
	Long	115°W	125°W	130°W	130°W	115°W
	Height,m	-46	-38	-37	-59	-70
South Pacific	Lat	40°S	75°S	70°S	70°S	70°S
	Long	120°E	160°W	170°W	180°W	170°W
	Height,m	-42	-60	-53	-45	-75
North Pacific	Lat				45°N	40°N
	Long				175°W	175°W
	Height,m				-22	-35
West Atlantic	Lat	15°N	20°N	25°N	30°N	30°N
	Long	55°W	55°W	70°W	75°W	70°W
	Height,m	-23	-41	-29	-70	-45

Table 6-1. Geoid Features (after Anderle, 1967)

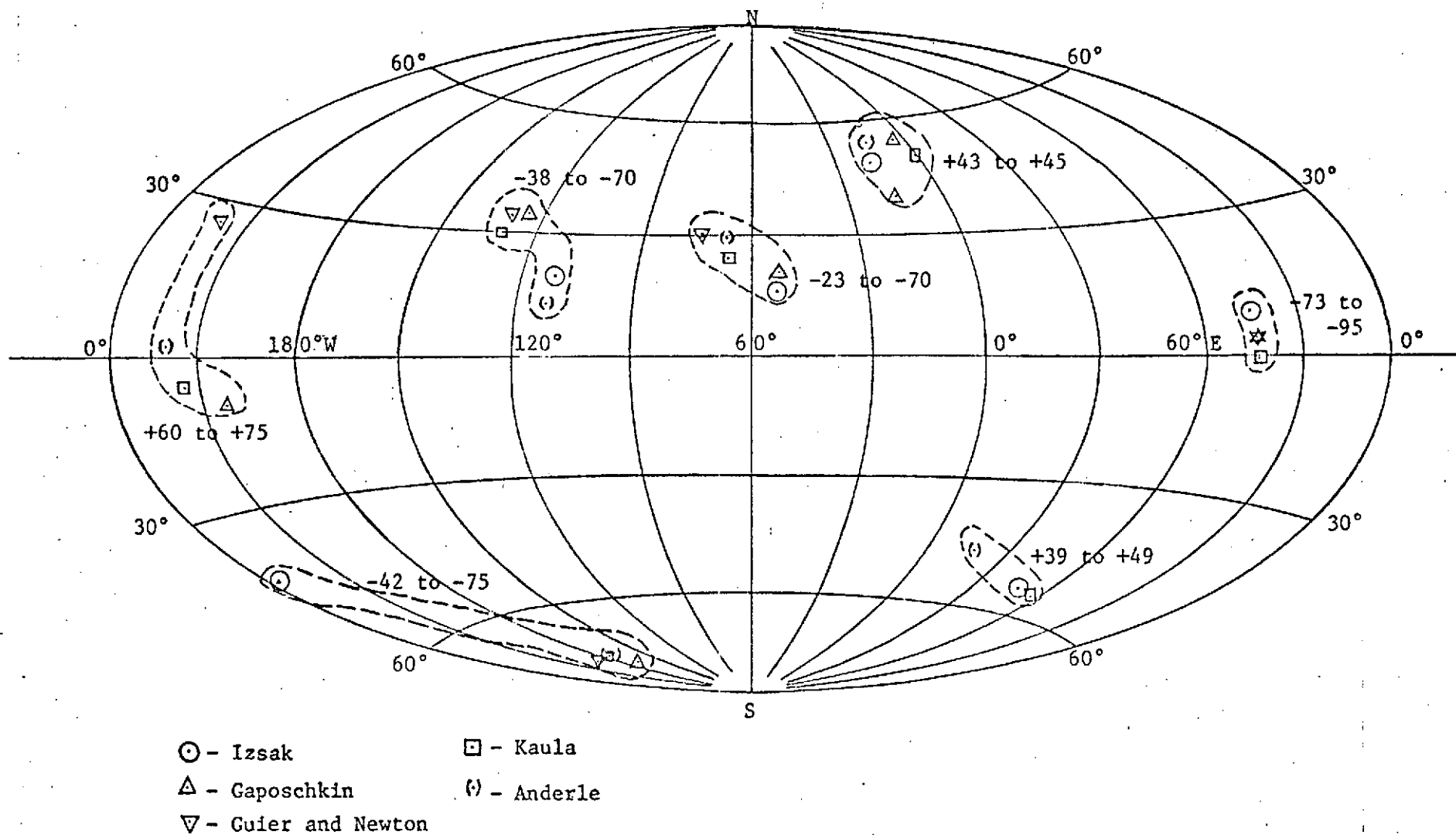


Figure 6-4. Geoidal Feature Locations as Given in Five Versions of the Geoid

It may be that the only reliable method of separating these two effects will be to schedule exactly repetitive data takes and to attribute those that vary in time to non-geoidal topography.

(b) Gulf Stream Surface Topography Shape Uncertainty

In Figure 6-3, Defant's estimate of current-induced surface topography in the Western North Atlantic is shown. Figure 6-5, (from Reference 6) shows sea-surface topography for the same region as obtained from ship drift measurements (the contours shown are annual means). The shape of a transverse section across the Gulf Stream off Cape Hatteras or Wallops Flight Center is obviously going to be vastly different in the two plots. Equally obvious is the fact that an optimum filter designed to extract a characteristic predicted from Defant's estimate, from satellite altimeter data, is going to be far from optimum in extraction of the characteristic depicted in Figure 6-5. Figure 6-6 shows the elevation shape for the two plots for a cut across the Gulf Stream between 36.5°N and 38.5°N, near 68.5°W.

(c) Gulf Stream Western Boundary Complexity

As can be seen from the IR images of the Gulf Stream, its thermal western boundary is quite variable and complex. Assuming that this is also true of its physical characteristics, it may be that the relatively clean shape characteristic predicted by either Defant or Sturges may rarely if ever be seen in satellite altimeter data, unless the data from several repetitive passes is averaged. This still further complicates the filtering problem and could result in the complete elimination of optimal filtering as the desired approach.

(d) Correlation Between Location of Thermal and Physical Characteristics

It may well be that some of the complexity of Gulf Stream boundaries observed by infrared radiometers is attributable to factors which influence the thermal signature of the ocean's surface but not its physical signature. It is known that radiometric data is affected by atmospheric transmissivity characteristics, by surface contaminants, and (more obviously) by cloud contamination (sometimes invisible in images). Generally, these effects are thought to be small compared to the scale of the observed complexities. However, little quantitative investigation of the correlation between

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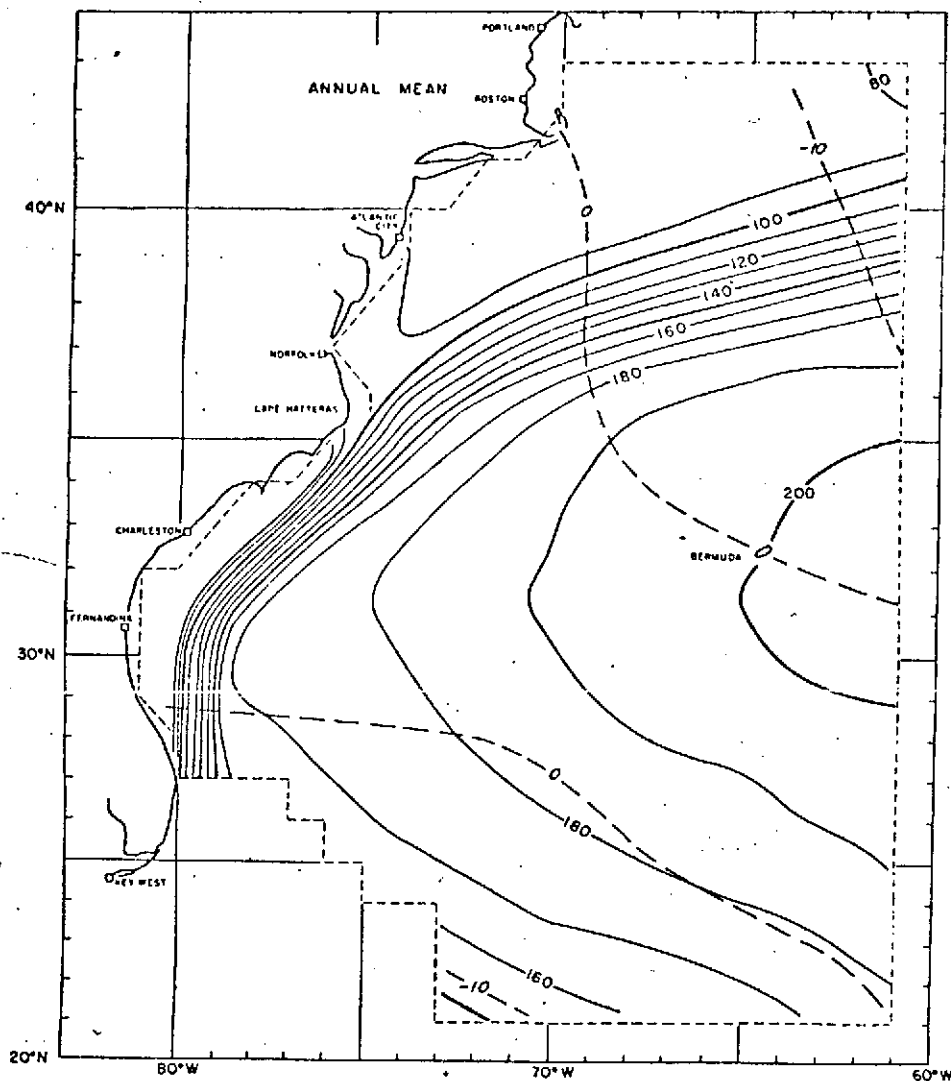


Figure 6-5. Sea-surface topography from ship drift: annual mean. The continuous contours show topography of the sea surface in cm based on heights calculated from ship drift; the numerical values are relative to an annual mean of 200 cm at Bermuda. The dashed contours are an estimate of the part of the computed ship-drift topography caused by the wind alone. The contour interval is 10cm; the scale is  $1:20 \times 10^6$  at 30° on Mercator projection.

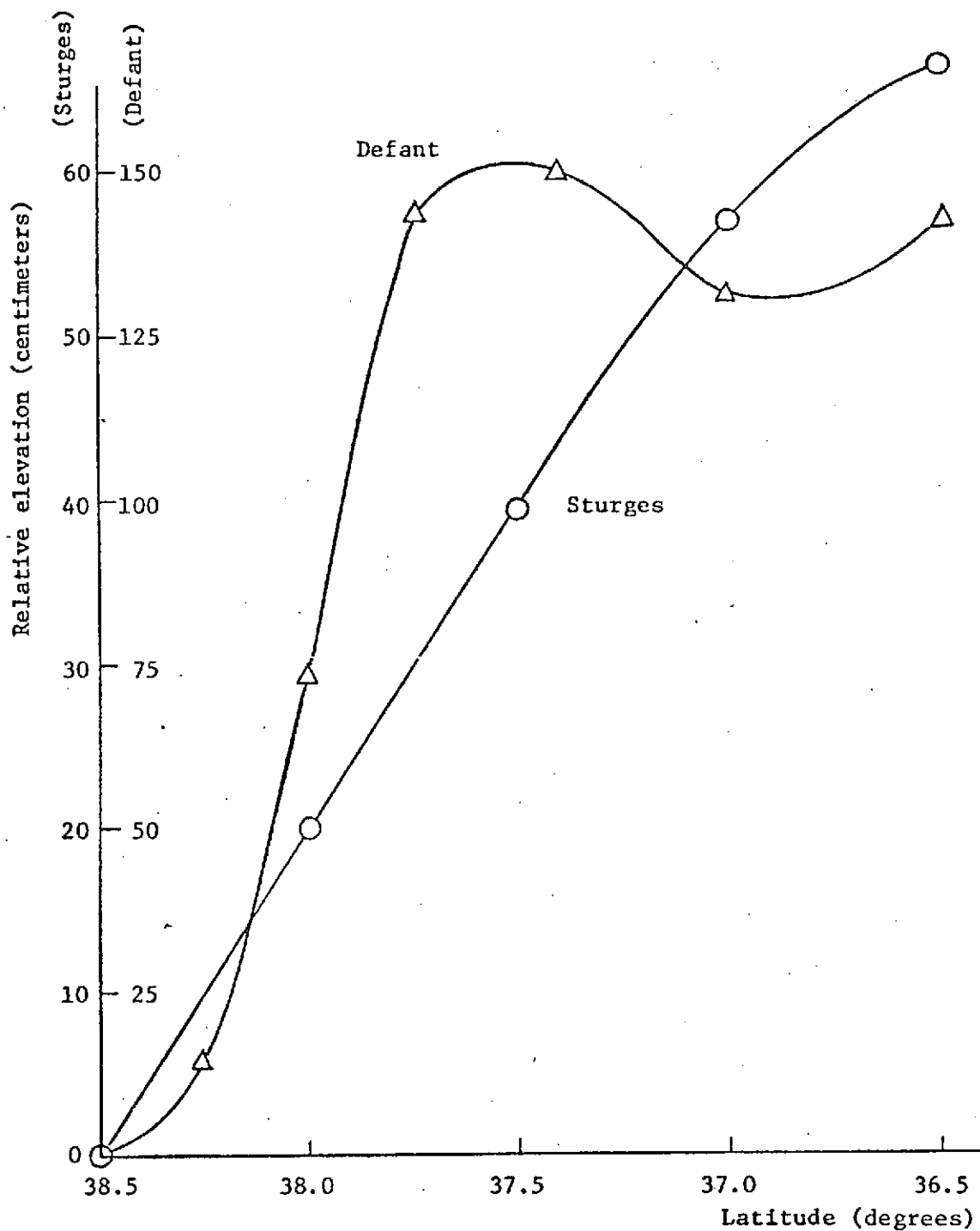


Figure 6-6. Predicted Elevation Characteristics For Two Cuts Across The Surface Of The Gulf Stream

thermal and physical characteristics has been accomplished to date, and this question is largely unanswered. Hansen and Maul (Reference 17) have reported differences of the order of 15 kilometers in surface temperature indications of current locations and in temperature-at-depth indications. Although this still does not treat the thermal/physical relative situation directly, it is felt that the reliability of the at-depth indicator used in that work and the simultaneity of the at-depth and surface measurements should yield reasonably accurate relative location results. However, the question of surface physical feature location relative to at-depth physical feature location is still untreated.



Appendix A.

This appendix contains charts which show the S-193 altimeter passes of interest to this investigation.

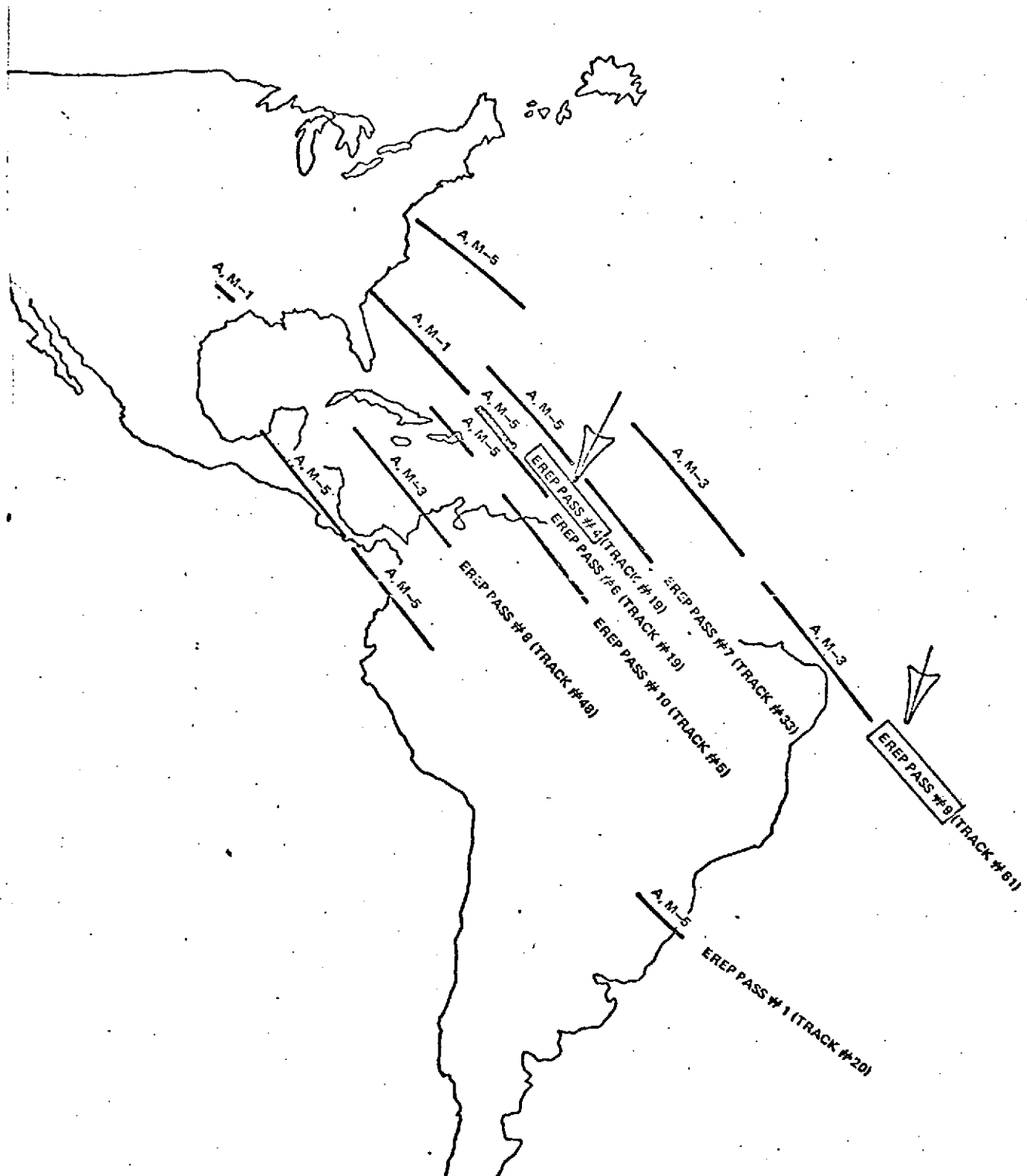


Figure A-1  
S-193 - Skylab SL-2 Data Takes Altimeter Modes 1,3 and 5  
(from Reference 25)

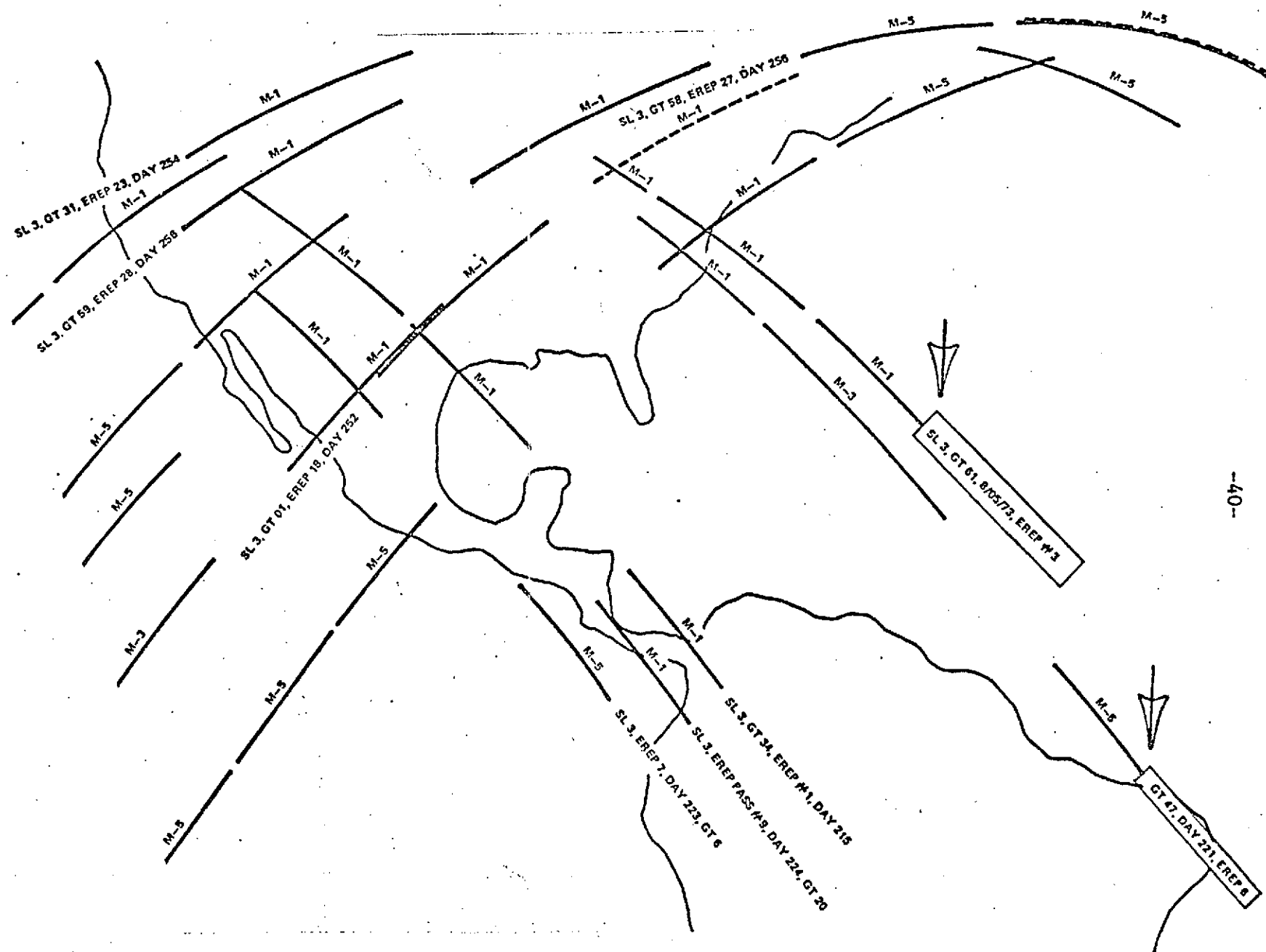


Figure A-2

S-193 Skylab SL-3 Data Takes Altimeter Modes 1,3,5 (from Reference 25)

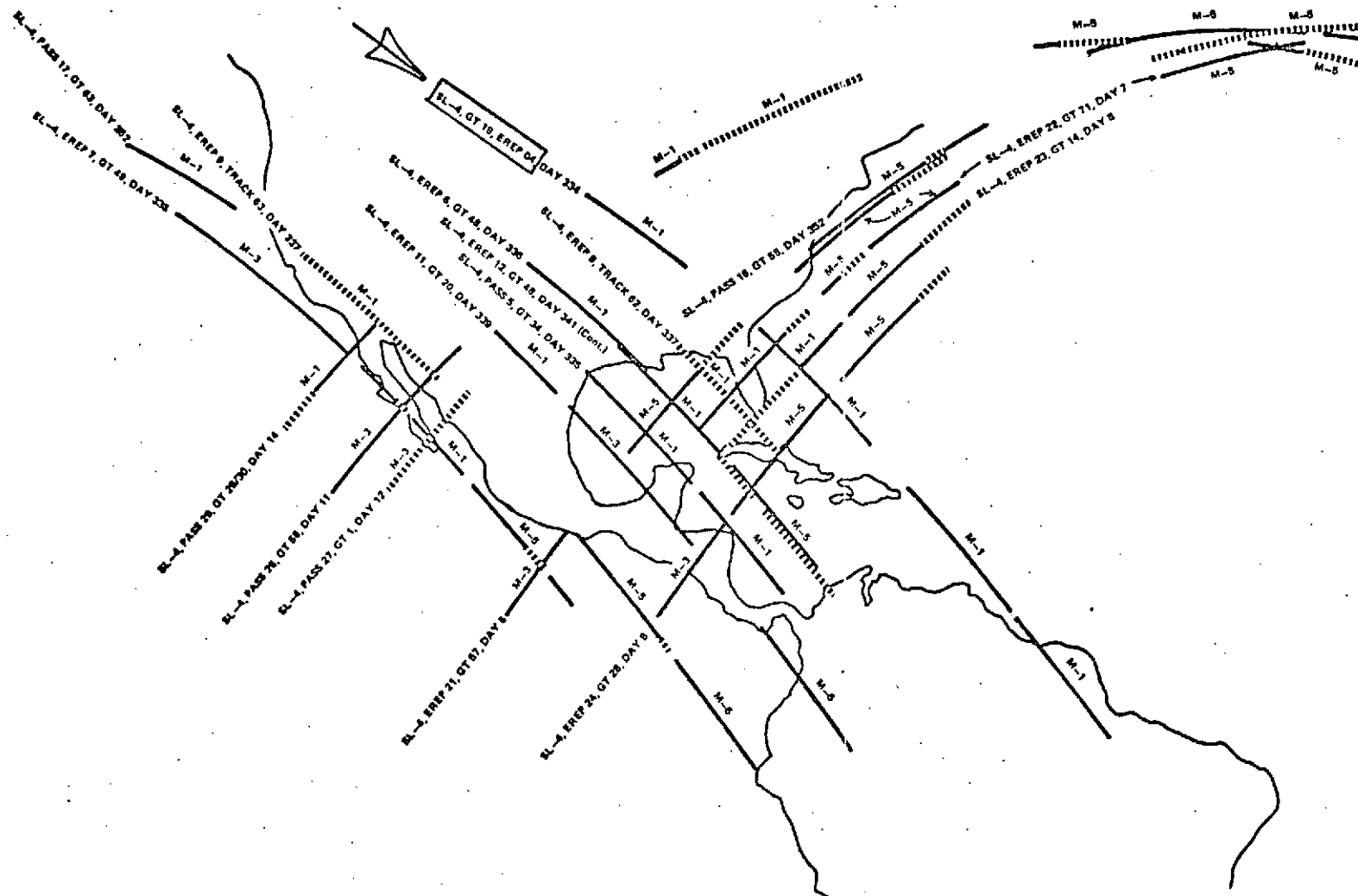
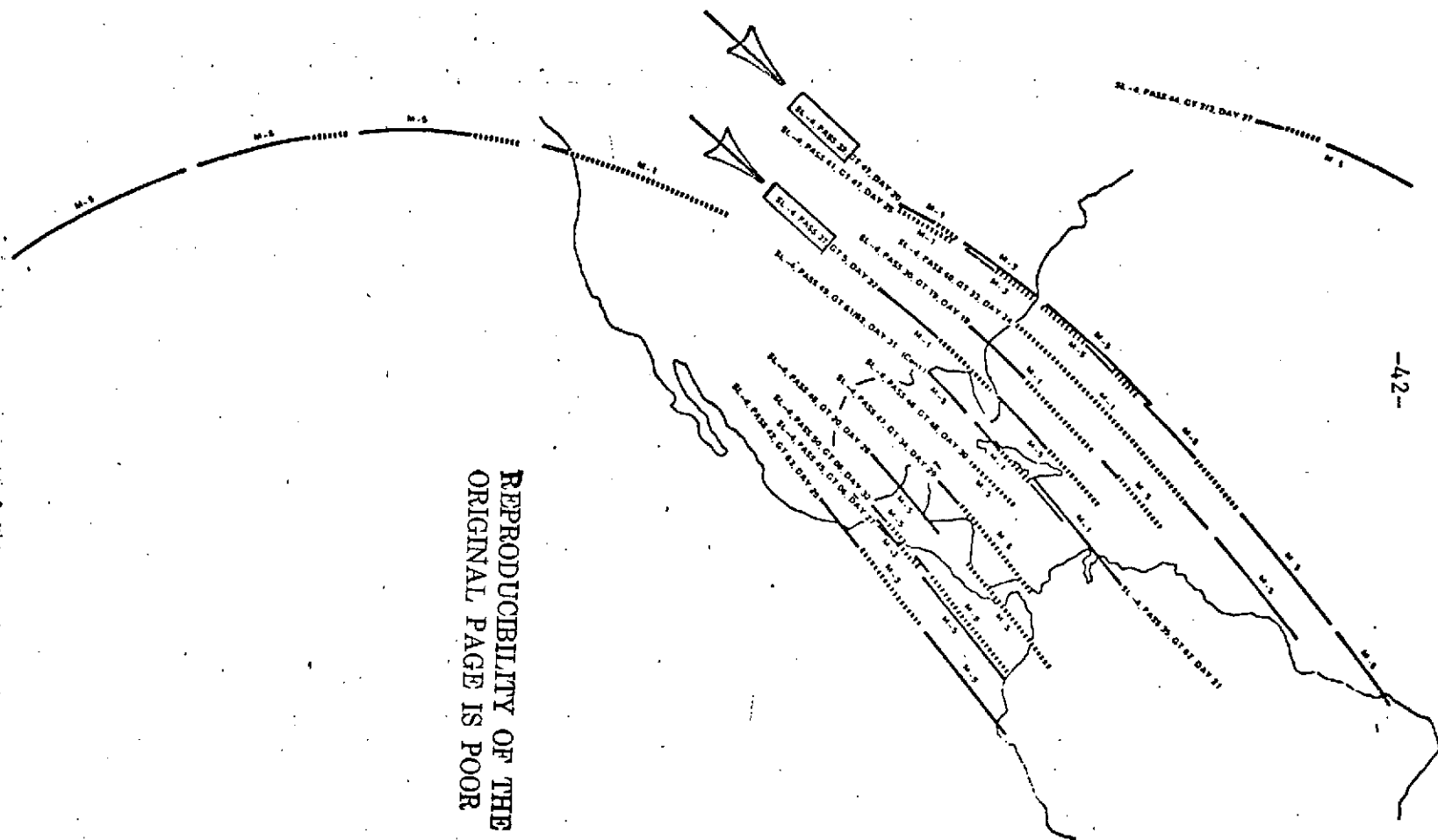


Figure A-3

S-193 Skylab SL-4 Data Takes Altimeter Modes 1,3 and 5 (from Reference 25)



S-193 Skylab SL-4 Data Takes Altimeter Modes 1,3 and 5 (Cont.) (from Reference 25)

## Appendix B

The data filtering procedure discussed here is based on the filter solution given in Reference 21. This reference contains a derivation of the transfer function and impulse response description for optimally filtering altitude data, based on the Wiener-Hopf theory and through use of a geoidal power-spectral-density obtained from S-193 altimeter observations. These results indicated that instrument random measurement errors limited the achievable geoidal resolution to wavelengths equal to or greater than 30-40 km. Lacking explicit information on the Gulf Stream signature, we felt that the Wiener filter represented the highest resolution filtering procedure justifiable for the S-193 data. The impulse response corresponding to the optimal filter given in Reference 21 was not suitable for passes near Cape Hatteras because the proximity of the Gulf Stream to the coast would not permit filter initialization prior to entry into the stream itself. Instead, the transfer function from Reference 21 was used as a basis for designing a finite-impulse-response (FIR) realization. A search of the FIR filter literature revealed that the existing design criteria were not appropriate to our problem. (The realization procedures given in the literature are generally based on equi-ripple or aliasing criteria.) We then decided to utilize a "window approach" (Reference 22) in designing a FIR filter and selected a rapidly truncating impulse response function whose transfer function matched the desired Wiener filter at the half-power point and whose frequency domain first sidelobes were at least 20 dB below passband response. This led to choice of a  $(\sin x)/(x-x^3)$  transfer function.

Specific characteristics of the resulting impulse response are as follows: For the input data  $x(t)$  available on an eight-per-frame basis, the filtered output  $y(t)$  is given by

$$y(t) = \sum_{i=-13}^{13} w_i x(t + i\Delta t)$$

where  $\Delta t$  = raw data period. The weights  $w_i$  are symmetrical about zero ( $w_i = w_{-i}$ ) and sum to unity;  $w_0 = .072$  and the other weights are:

<u>1</u>	<u>w<sub>1</sub></u>	<u>1</u>	<u>w<sub>1</sub></u>
1	.0705	7	.0355
2	.068	8	.028
3	.0635	9	.02
4	.058	10	.013
5	.0515	11	.008
6	.0435	12	.0035
		13	.001

Note that the above filter has a non-zero impulse response over a time span of ~3.5 seconds, in contrast to the much slower convergence properties of the Wiener filter.

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